Investigation on Thermal Conductivity, Viscosity and Stability of Nanofluids

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<table>
<thead>
<tr>
<th>Approved</th>
<th>Examiner</th>
<th>Supervisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.06.2012</td>
<td>Björn Palm</td>
<td>Ehsan Bitaraf Haghighi</td>
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<td>Rahmatollah Khodabandeh</td>
</tr>
</tbody>
</table>

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<th>Commissioner</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Abstract

In this thesis, two important thermo-physical properties of nanofluids: thermal conductivity and viscosity together with shelf stability of them are investigated. Nanofluids are defined as colloidal suspension of solid particles with the size of lower than 100 nanometer. Thermal conductivity, viscosity and stability of nanofluids were measured by means of TPS method, rotational method and sedimentation balance method, respectively. TPS analyzer and viscometer were calibrated in the early stage and all measured data were in the reasonable range. Effect of some parameters including temperature, concentration, size, shape, alcohol addition and sonication time has been studied on thermal conductivity and viscosity of nanofluids. It has been concluded that increasing temperature, concentration and sonication time can lead to thermal conductivity enhancement while increasing amount of alcohol can decrease thermal conductivity of nanofluids. Generally, tests relating viscosity of nanofluids revealed that increasing concentration increases viscosity; however, increasing other investigated parameters such as temperature, sonication time and amount of alcohol decrease viscosity. In both cases, increasing size of nanofluid results in thermal conductivity and viscosity reduction up to specific size (250 nm) while big particle size (800 nm) increases thermal conductivity and viscosity, drastically. In addition, silver nanofluid with fiber shaped nanoparticles showed higher thermal conductivity and viscosity compared to one with spherical shape nanoparticles. Furthermore, effect of concentration and sonication time have been inspected on stability of nanofluids. Test results indicated that increasing concentration speeds up sedimentation of nanoparticles while bath sonication of nanofluid brings about lower weight for settled particles. Considering relative thermal conductivity to relative viscosity of some nanofluids exposes that ascending or descending behavior of graph can result in some preliminary evaluation regarding applicability of nanofluids as coolant. It can be stated that ascending trend shows better applicability of the sample in higher temperatures while it is opposite for descending trend. Meanwhile, it can be declared that higher value for this factor shows more applicable nanofluid with higher thermal conductivity and less viscosity. Finally, it has been shown that sedimentation causes reduction of thermal conductivity as well as viscosity. For further research activities, it would be suggested to focus more on microscopic investigation regarding behavior of nanofluids besides macroscopic study.
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List of Figures

Figure 1.1: Common basefluids, nanoparticles, and surfactants for synthesizing nanofluid ........................................ 3
Figure 2.1: Share of different methods in literature ............................................... 11
Figure 2.2: Schematic of transient hot-wire experimental setup ...................................... 11
Figure 2.3: Schematic of transient temperature oscillation technique ................................... 13
Figure 2.4: Falling ball viscometers schematic ......................................................... 19
Figure 2.5: Falling ball viscometers schematic ......................................................... 20
Figure 2.6: Coaxial cylinder viscometers schematic .................................................... 21
Figure 2.7: Three bubble viscometers in different viscosity ranges ...................................... 22
Figure 3.1: Experimental setup of Transient Plane Source (TPS) method .......................... 28
Figure 3.2: Sample holder and sensor ........................................................................ 29
Figure 3.3: Thermal conductivity of water at different temperatures ................................. 29
Figure 3.4: Thermal conductivity of ethylene glycol (EG) at different temperatures .......... 30
Figure 3.5: Thermal conductivity of mixture of ethylene glycol and distilled water (50 vol%) at different temperatures ................................................................. 31
Figure 3.6: Location of seven thermocouples installed in thermal bath .............................. 32
Figure 3.7: Temperature monitoring of bath and sample holder over the time at T=20°C for dry shell .......................................................... 33
Figure 3.8: Average temperature of clamp, shell and bath compared to adjusted temperature at T=20°C for dry shell .............................................................. 33
Figure 3.9: Temperature monitoring of bath and sample holder over the time from T=20°C to T=30°C for dry shell ........................................................................ 34
Figure 3.10: Temperature monitoring of bath and sample holder over the time at T=30°C for dry shell ........................................................................ 34
Figure 3.11: Temperature difference from set point for dry shell ...................................... 36
Figure 3.12: Temperature monitoring of bath and sample holder over the time at T=30°C for wet shell .......................................................... 36
Figure 3.13: Temperature difference from set point for dry shell ...................................... 36
Figure 3.14: Temperature monitoring of bath and sample holder over the time at T=20°C for wet shell .......................................................... 36
Figure 3.15: Average temperature of clamp, shell and bath compared to adjusted temperature at T=20°C for wet shell .......................................................... 37
Figure 3.16: Temperature monitoring of bath and sample holder over the time from T=20°C to T=30°C for wet shell ........................................................................ 37
Figure 3.17: Temperature monitoring of bath and sample holder over the time at T=30°C for wet shell .......................................................... 38
Figure 3.18: Temperature difference from set point for wet shell ...................................... 39
Figure 3.19: Temperature difference from set point for dry and wet shell at different temperatures .......................................................... 39
Figure 3.20: Temperature monitoring of sample holder over the time from T=20°C to T=30°C for wet and dry shell ........................................................................ 40
Figure 3.21: Hot Disk sensor with Kapton insulation ........................................................ 41
Figure 3.22: Power/Time combinations for measuring thermal conductivity of DW at T=20°C .......................................................... 42
Figure 3.23: Confirmation of selected combination at T=20°C and comparing with NIST data .......................................................... 43
Figure 3.24: Power/Time combinations for measuring thermal conductivity of DW at T=30°C .......................................................... 43
Figure 3.25: Confirmation of selected combination at T=30°C and comparing with NIST data .......................................................... 44
Figure 3.26: Power/Time combinations for measuring thermal conductivity of DW at T=40°C .......................................................... 45
Figure 3.27: Confirmation of selected combination at T=40°C and comparing with NIST data .......................................................... 45
Figure 3.28: Power/Time combinations for measuring thermal conductivity of DW at T=50°C .......................................................... 46
Figure 3.29: Confirmation of selected combination at T=40°C and comparing with NIST data .......................................................... 47
Figure 3.30: Thermal conductivity of EG/CeO$_2$ nanofluids at different temperatures ........ 48
Figure 3.31: Thermal conductivity of AFN/CeO$_2$ nanofluids at different temperatures ........ 49
Figure 3.32: Thermal conductivity of DW/Al$_2$O$_3$ (9 wt%) at different times of sonication 50
Figure 3.33: Thermal conductivity of DW+AFN/Al$_2$O$_3$ (9 wt%) for different times of sonication 51
Figure 3.34: Thermal conductivity of and DW/Al$_2$O$_3$ (9 wt%)(left) and DW+AFN/Al$_2$O$_3$ (9 wt%)(right) at T=20°C for different particles sizes .......................................................... 52
Figure 3.35: Behavior of thermal conductivity of AFN/Al$_2$O$_3$ (9 wt%) at T=20°C for different particle sizes .......................................................... 52
Figure 3.36: Thermal conductivity of DW+EG/Ag (2 wt%) nanofluids at different temperatures 53
Figure 3.37: Thermal conductivity of different mixtures of DI+EtOH at T=20°C .................. 54
Figure 3.38: Thermal conductivity of different mixtures of DI+EtOH with Al₂O₃ (3 wt%) nanoparticles inside at T=20 °C................................................................. 55
Figure 3.39: Thermal conductivity of nanofluids with various nanoparticles at different temperatures................................................................. 56
Figure 3.40: Thermal conductivity of SiC nanofluids at different temperatures ................................................................................................. 57
Figure 3.41: Confirmation test of thermal conductivity for SiC nanofluids at T=20 °C................................................................. 58
Figure 4.1: Basic structure of a coaxial cylinder viscometer................................................................................................. 59
Figure 4.2: Different Spindle models ............................................................................................................................................... 60
Figure 4.3: Schematic diagram of DV-II+Pro and components................................................................................................. 61
Figure 4.4: Different parts of DV-II+Pro viscometer................................................................................................. 61
Figure 4.5: Cylinder shape Spindle of ULA ............................................................................................................................................... 62
Figure 4.6: Sample holder and cooling jacket of ULA ......................................................................................... 62
Figure 4.7: Viscosity of distilled water for different databases compared to KTH measurement ............................. 65
Figure 4.8: Deviation of KTH measurement for distilled water from different data bases ................................................................. 65
Figure 4.9: Average deviation of distilled water viscosity measurement at KTH from different databases ......................................................................................... 66
Figure 4.10: Viscosity of EG for different databases compared KTH measurement ................................................................. 67
Figure 4.11: Deviation of KTH measurement (EG) for distilled water from different data bases ................................................................. 68
Figure 4.12: Average deviation of KTH viscosity measurement (EG) from different databases ................................................................. 68
Figure 4.13: Viscosity of EG/DW (50 vol%) for different data bases compared KTH measurement ............................. 69
Figure 4.14: Location of theromocouples connection on the spindle/inside the sample holder ................................................................. 71
Figure 4.15: Bath performance for viscometer at T=20 °C ................................................................................................. 71
Figure 4.16: Bath performance average temperatures for viscometer at T=20 °C ................................................................. 72
Figure 4.17: Bath performance for viscometer from temperature of 20 °C to 30 °C ................................................................. 73
Figure 4.18: Bath performance for viscometer at T=30 °C ................................................................................................. 73
Figure 4.19: Bath performance average temperatures for viscometer at T=30 °C ................................................................. 74
Figure 4.20: Bath performance, average deviation from the set point at different temperatures ................................................................. 75
Figure 4.21: Viscosity of DW+AFN/CeO₂ (9 wt%) versus shear rate at different temperatures ................................................................. 77
Figure 4.22: Shear stress of DW+AFN/CeO₂ (9 wt%) versus shear rate at different temperatures ................................................................. 77
Figure 4.23: Viscosity of DEG/Cu (0.6 wt%) versus shear rate at different temperatures ................................................................. 78
Figure 4.24: Shear stress of DEG/Cu (0.6 wt%) versus shear rate at different temperatures ................................................................. 78
Figure 4.25: Shear stress of DW+AFN/Al₂O₃ (9 wt%) versus shear rate at different temperatures ................................................................. 79
Figure 4.26: Viscosity of AFN/CeO₂ 1, 2 and 3 wt% versus temperatures ................................................................................................. 80
Figure 4.27: Viscosity increment of AFN/CeO₂ 1, 2 and 3 wt% at different temperatures ................................................................. 80
Figure 4.28: Viscosity of AFN/CeO₂ 1, 2 and 3 wt% versus shear rate at two different temperatures ................................................................. 81
Figure 4.29: Viscosity of DW+EG/Ag (2 wt%) nanoparticles at different temperatures ................................................................. 82
Figure 4.30: Viscosity of DW/Al₂O₃ (9 wt%) versus shear rate at different temperatures ................................................................. 83
Figure 4.31: Viscosity of AFN+DW/Al₂O₃ (9 wt%) versus shear rate at T=20 °C ................................................................. 84
Figure 4.32: Viscosity of AFN+DW/Al₂O₃ (9 wt%) for different particle size at T=20 °C ................................................................. 84
Figure 4.33: Viscosity of AFN+DW/Al₂O₃ (9 wt%) at different temperatures ................................................................. 85
Figure 4.34: Viscosity increment of AFN+DW/Al₂O₃ (9 wt%) at different temperatures ................................................................. 86
Figure 4.35: Viscosity of different mixtures of DI+EtOH at T=20°C versus shear rate ................................................................. 86
Figure 4.36: Viscosity of different mixtures of DI+EtOH at T=20°C ................................................................. 87
Figure 4.37: Viscosity of different mixtures of DI+EtOH with Al₂O₃ (3 wt%) at T=20°C versus shear rate ................................................................. 88
Figure 4.38: Viscosity of different mixtures of DI+EtOH with Al₂O₃ (3 wt%) nanoparticles inside at T=20°C ................................................................................................. 88
Figure 4.39: Viscosity of DW/Al₂O₃ (9 wt%) at different sonication time ................................................................................................. 89
Figure 4.40: Viscosity of DW+AFN/Al₂O₃ (9 wt%) at different sonication time ................................................................................................. 90
Figure 4.41: Viscosity of different nanofluids versus temperature ................................................................................................. 91
Figure 4.42: Viscosity of AFN/CeO₂ (1 wt%) versus shear rate at different temperatures ................................................................. 92
Figure 5.1: First experimental setup for measuring stability (left), frame and sample holder on the balance (right) ................................................................................................. 93
Figure 5.2: Sedimentation of AFN/CeO₂ nanofluid during 7 days ................................................................................................. 94
Figure 5.3: Scheme of experimental setup for stability evaluation ................................................................................................. 94
Figure 5.4: Modified instrument to measure sedimentation rate of nanofluids ................................................................................................. 95
Figure 5.5: Sedimentation of china clay type I, II and III ................................................................................................. 96
Figure 5.6: Sedimentation of china clay type I, II and III in 120 minutes ........................................ 97
Figure 5.7: Sedimentation rate of china clay type I, II and III .......................................................... 97
Figure 5.8: Sedimentation rate of china clay type I, II and III .......................................................... 98
Figure 5.9: Sedimentation of Al_{2}O_{3} water-based nanofluids (3, 6, and 9wt%) ................................ 98
Figure 5.10: Sedimentation rate for Al_{2}O_{3} water-based nanofluids (3, 6, and 9wt%) ...................... 99
Figure 5.11: Sedimentation for CeO_{2} (1 and 2 wt%) in ethylene glycol ........................................... 99
Figure 5.12: Sedimentation rate for CeO_{2} (1 and 2 wt%) in ethylene glycol ...................................... 100
Figure 5.13: Sedimentation for CeO_{2} in the mixture of ethylene glycol & DW (50% vol) before and after sonication ................................................................. 100
Figure 6.1: Relative thermal conductivity to relative viscosity of DW+AFN/ Al_{2}O_{3} nanofluid at different temperatures .......................................................................................................... 101
Figure 6.2: Relative thermal conductivity to relative viscosity of DW+EG/Ag nanofluid at different temperatures ................................................................................................................ 102
Figure 6.3: Relative thermal conductivity to relative viscosity of AFN/CeO_{2} nanofluid at different temperatures ................................................................................................................... 104
Figure 6.4: Thermal conductivity of EG+DW / Ag (2 wt%)nanofluid at different temperatures............. 104
Figure 6.5: Viscosity of DW+AFN/CeO_{2} (9 wt%) over 200 minutes .................................................. 106
Figure A.1: Temperature monitoring of bath and sample holder over the time from T=30°C to T=40°C for dry shell ................................................................. 120
Figure A.2: Temperature monitoring of bath and sample holder over the time at T=40°C for dry shell 120
Figure A.3: Average temperature of clamp, shell and bath compared to adjusted temperature at T=40°C for dry shell ........................................................................................................ 121
Figure A.4: Temperature monitoring of bath and sample holder over the time from T=40°C to T=50°C for dry shell ................................................................. 121
Figure A.5: Temperature monitoring of bath and sample holder over the time at T=50°C for dry shell 122
Figure A.6: Average temperature of clamp, shell and bath compared to adjusted temperature at T=50°C for dry shell ........................................................................................................ 122
Figure A.7: Temperature monitoring of bath and sample holder over the time from T=30°C to T=40°C for wet shell .................................................................................................................. 123
Figure A.8: Temperature monitoring of bath and sample holder over the time at T=40°C for wet shell 123
Figure A.9: Average temperature of clamp, shell and bath compared to adjusted temperature at T=40°C for wet shell ........................................................................................................ 124
Figure A.10: Temperature monitoring of bath and sample holder over the time from T=40°C to T=50°C for wet shell .................................................................................................................. 124
Figure A.11: Temperature monitoring of bath and sample holder over the time at T=50°C for wet shell 125
Figure A.12: Average temperature of clamp, shell and bath compared to adjusted temperature at T=50°C for wet shell ........................................................................................................ 125
Figure B.1: Bath performance for viscometer from temperature of 30°C to 40°C ............................ 126
Figure B.2: Temperature of each section at set point of T=40°C ....................................................... 126
Figure B.3: Bath performance average temperature at T=40°C ....................................................... 127
Figure B.4: Bath performance for viscometer from temperature of 40°C to 50°C ............................ 127
Figure B.5: Bath performance at T=50°C ............................................................................................. 128
Figure B.6: Temperature of each section at set point of at T=50°C .................................................. 128
Figure B.7: Bath performance average temperature at T=50°C ....................................................... 129
Figure B.8: Bath performance for viscometer from temperature of 50°C to 60°C ............................ 129
Figure B.9: Bath performance at T=60°C ............................................................................................. 130
Figure B.10: Temperature of each section at set point of at T=60°C .................................................. 130
Figure B.11: Bath performance average temperature at T=60°C ....................................................... 131
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Zeta potential absolute values and stability</td>
<td>26</td>
</tr>
<tr>
<td>3.1</td>
<td>Thermal conductivity of distilled water</td>
<td>31</td>
</tr>
<tr>
<td>3.2</td>
<td>Temperature difference from set point for dry shell</td>
<td>35</td>
</tr>
<tr>
<td>3.3</td>
<td>Temperature difference from set point for wet shell</td>
<td>38</td>
</tr>
<tr>
<td>3.4</td>
<td>Selected power and time combination for different temperatures</td>
<td>47</td>
</tr>
<tr>
<td>3.5</td>
<td>Thermal conductivity enhancement of EG/CeO$_2$ nanofluids at different temperatures</td>
<td>49</td>
</tr>
<tr>
<td>3.6</td>
<td>Thermal conductivity enhancement of AFN/CeO$_2$ nanofluids at different temperatures</td>
<td>50</td>
</tr>
<tr>
<td>3.7</td>
<td>Information of nanofluids for sonication time test</td>
<td>50</td>
</tr>
<tr>
<td>3.8</td>
<td>Thermal conductivity enhancement of DW+EG/Ag (2 wt%) nanofluids at different temperatures</td>
<td>53</td>
</tr>
<tr>
<td>3.9</td>
<td>Thermal conductivity of DI+EtOH/Al$_2$O$_3$ nanofluid at T=20 °C</td>
<td>55</td>
</tr>
<tr>
<td>3.10</td>
<td>Thermal conductivity enhancement of nanofluids with various nanoparticles at different temperatures</td>
<td>56</td>
</tr>
<tr>
<td>3.11</td>
<td>Information of SiC nanofluids and their basefluids</td>
<td>57</td>
</tr>
<tr>
<td>3.12</td>
<td>Thermal conductivity enhancement of SiC nanofluids compared to basefluid</td>
<td>58</td>
</tr>
<tr>
<td>4.1</td>
<td>Different Spindle models</td>
<td>60</td>
</tr>
<tr>
<td>4.2</td>
<td>Brookfield DV-II+Pro viscometer features</td>
<td>62</td>
</tr>
<tr>
<td>4.3</td>
<td>Bath performance, percentage of deviation from the set point at different temperatures</td>
<td>75</td>
</tr>
<tr>
<td>4.4</td>
<td>percentage of viscosity increment of AFN/CeO$_2$ 1, 2 and 3 wt% at different temperatures</td>
<td>81</td>
</tr>
<tr>
<td>4.5</td>
<td>percentage of viscosity increment of DW+EG/Ag (2 wt%) at different temperatures</td>
<td>82</td>
</tr>
<tr>
<td>4.6</td>
<td>percentage of viscosity increment of AFN+DW/Al$_2$O$_3$ (9 wt%) for different particle size at T=20 °C</td>
<td>85</td>
</tr>
<tr>
<td>4.7</td>
<td>Viscosity increment of water adding EtOH surfactant at T=20 °C</td>
<td>87</td>
</tr>
<tr>
<td>4.8</td>
<td>Percentage of viscosity increment for different mixtures of DI+EtOH with Al$_2$O$_3$ (3 wt%) at T=20°C</td>
<td>89</td>
</tr>
<tr>
<td>4.9</td>
<td>Viscosity increment of water adding EtOH surfactant at T=20 °C</td>
<td>90</td>
</tr>
<tr>
<td>4.10</td>
<td>Percentage of Viscosity increment of DW+AFN/Al$_2$O$_3$ (9 wt%) at different sonication time</td>
<td>91</td>
</tr>
<tr>
<td>4.11</td>
<td>Percentage of Viscosity increment of different nanofluids versus temperature</td>
<td>92</td>
</tr>
<tr>
<td>5.1</td>
<td>Information of nanofluids used in stability measurement experiments</td>
<td>96</td>
</tr>
<tr>
<td>6.1</td>
<td>Thermal conductivity enhancement of EG+DW / Ag (2 wt%) nanofluid</td>
<td>106</td>
</tr>
</tbody>
</table>
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>Damping constant</td>
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<tr>
<td>$\Delta$</td>
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<td>[-]</td>
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<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
<td>[cP]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Velocity</td>
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<td>$\Omega$</td>
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<td>$A$</td>
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<tr>
<td>$F_s$</td>
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<tr>
<td>$g$</td>
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<tr>
<td>$h$</td>
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<td>[m]</td>
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<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
<td>[W/m.K]</td>
</tr>
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<td>$K$</td>
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<td>$P$</td>
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<td>$V$</td>
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<tr>
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</table>

### Abbreviation

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
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<tr>
<td>AFN</td>
<td>Antifrogen N</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Networks</td>
</tr>
<tr>
<td>CC</td>
<td>China Clay</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nanotube</td>
</tr>
<tr>
<td>CTAB</td>
<td>Cetyl Trimethylammonium Bromide</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DEG</td>
<td>Diethylene Glycol</td>
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<tr>
<td>DI</td>
<td>Deionized Water</td>
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DTAB  Dodecyl Trimethylammonium Bromide
DW    Distilled Water
EG    Ethylene Glycol
EtOH  Alcohol
HC    Hamilton-Crosser
HCTAB Hexadecyltrimethylammoniumbromide
ICE   Internal Combustion Engine
MCNT  Multiwall Carbon Nanotube
PC    Personal Computer
PVP   Polyvinylpyrrolidone
SDBS  Sodium Dodecyl Benzene Sulfonate
SDS   Sodium Dodecylsulfate
SEM   Scanning Electron Microscopy
SOCT  Sodium Octanoate
SSA   Specific Surface Area
TC    Thermal Conductivity
TEM   Transmission Electron Microscopy
THW   Transient Hot Wire
TPS   Transient Plane Source
vol   Volume concentration
wt    Weight percentage

Subscripts
  a    Air
  bf   Basefluid
  L    Liquid
  nf   Nanofluid
  p    Particle
  r    Relative
  s    Suspension
  T    Total
Table of Content

Abstract.................................................................................................................................................. III
Acknowledgment .................................................................................................................................. IV
List of Figures ......................................................................................................................................... V
List of Tables ........................................................................................................................................ VIII
Nomenclature.......................................................................................................................................... IX
1. Introduction ......................................................................................................................................... 1
   1.1. About Nanofluids ....................................................................................................................... 1
   1.2. Preparation of Nanofluids ........................................................................................................... 2
   1.3. Objective of present research ..................................................................................................... 4
2. Literature Review ................................................................................................................................ 5
   2.1. Thermal Conductivity in Literature ........................................................................................... 5
      2.1.1. Effective parameters on thermal conductivity ...................................................................... 5
      2.1.1.1. Morphology ..................................................................................................................... 5
      2.1.1.2. Temperature .................................................................................................................... 6
      2.1.1.3. Concentration .................................................................................................................. 6
      2.1.1.4. Motion ............................................................................................................................ 6
      2.1.1.5. Thermal conductivity of nanoparticles............................................................................. 7
      2.1.1.6. Thermal conductivity of basefluid...................................................................................... 7
      2.1.1.7. Clustering.......................................................................................................................... 8
      2.1.1.7. Acidity (pH) ..................................................................................................................... 8
      2.1.1.7. Additives........................................................................................................................... 8
      2.1.2. Measurement techniques for thermal conductivity .............................................................. 10
         2.1.2.1. Transient hot-wire (THW) method ................................................................................. 11
         2.1.2.2. Transient Plane Source (TPS) method ......................................................................... 12
         2.1.2.3. Steady-state parallel-plate method ................................................................................. 12
         2.1.2.4. Cylindrical cell method ................................................................................................ 13
         2.1.2.5. Temperature Oscillation method ................................................................................... 13
         2.1.2.6. 3σ method ...................................................................................................................... 14
         2.1.2.7. Thermal comparator method .......................................................................................... 14
   2.2. Viscosity of Nanofluids .................................................................................................................. 15
      2.2.1. Effective parameters on viscosity........................................................................................... 15
         2.2.1.1. Temperature ................................................................................................................... 15
         2.2.1.2. Volume fraction .............................................................................................................. 16
         2.2.1.3. Morphology .................................................................................................................... 16
2.2.1.4. Shear rate .................................................................................................................. 17
2.2.1.4. Dispersion method, stabilizers .................................................................................. 18
2.2.2. Viscosity Measurement Methods .................................................................................. 18
2.2.2.1. Flow Type Viscometers ......................................................................................... 18
2.2.2.2. Drag Type Viscometers ......................................................................................... 20
2.2.2.3. Vibrational/Oscillating Viscometers ...................................................................... 22
2.3. Stability .......................................................................................................................... 24
2.3.1. Effective parameters on stability .................................................................................. 24
2.3.1.1. Addition of surfactant ............................................................................................ 25
2.3.1.2. pH Control ........................................................................................................... 25
2.3.1.3. Ultrasonic agitation (vibration) ............................................................................. 25
2.3.2. Stability Evaluation Method ........................................................................................ 26
2.3.2.1. UV–Vis spectrophotometer ................................................................................... 26
2.3.2.2. Zeta potential test ................................................................................................ 26
2.3.2.3. Sedimentation photograph capturing .................................................................... 27
2.3.2.4. TEM (Transmission Electron Microscopy) and SEM (Scanning Electron Microscopy) ................................................................. 27
2.3.2.5. Sedimentation balance method ............................................................................ 27
2.3.2.6. 3σ method ............................................................................................................ 27
3. Thermal Conductivity Measurement .................................................................................. 28
3.1. Experimental result for thermal conductivity ................................................................. 28
3.1.1. Transient plane source method .................................................................................. 28
3.1.2. Calibration of the instrument ..................................................................................... 29
3.1.3. Thermal Bath Performance ........................................................................................ 32
3.1.3.1. Dry shell .............................................................................................................. 32
3.1.3.2. Wet Shell ............................................................................................................. 32
3.1.4. Power and Time Combination .................................................................................... 41
3.1.5. Thermal Conductivity Measurement of Nanofluids .................................................. 48
3.1.5.1. Particle Concentration .......................................................................................... 48
3.1.5.2. Sonication Time .................................................................................................. 50
3.1.5.3. Particle size ......................................................................................................... 51
3.1.5.4. Particle Shape ..................................................................................................... 53
3.1.5.5. Alcohol ............................................................................................................... 54
3.1.5.6. Temperature ........................................................................................................ 55
3.1.5.7. Importance of synthesis ....................................................................................... 56
4. Viscosity Measurement .................................................................................................... 59
4.1. Experimental result for viscosity .................................................................................. 59
4.1.1. Rotating cylinder method (Brookfield DV-II+ Pro viscometer) .............................................. 59
4.1.1.1. The procedure .................................................................................................................. 60
4.1.1.2. Brookfield DV-II+ Pro viscometer characteristics ............................................................. 61
4.1.1.3. Two important considerations ......................................................................................... 63
4.1.2. Instrument Calibration ......................................................................................................... 64
4.1.3. Thermal Bath performance of Viscometer ............................................................................. 70
4.1.4. Experimental Studies on Viscosity of Nanofluids ................................................................. 76
4.1.4.1. Different type of viscosity ............................................................................................... 76
4.1.4.2. Measurement of some Newtonian and non-Newtonian Basefluids/Nanofluids ............... 76
4.1.4.3. Considering effective parameters on Viscosity ................................................................. 79
5. Stability of Nanofluids .................................................................................................................. 93
5.1. Evaluation method .................................................................................................................... 93
5.2. Experimental result ................................................................................................................... 95
  5.2.1. Effect of particles concentration on stability ................................................................. 96
  5.2.2. Effect of particles sonication on stability ......................................................................... 100
6. Integrated consideration of nanofluid properties ........................................................................ 102
  6.1. Thermal conductivity and viscosity ..................................................................................... 102
  6.2. Stability , thermal conductivity and viscosity ..................................................................... 105
    6.2.1. Sedimentation and thermal conductivity ................................................................. 105
    6.2.2. Sedimentation and viscosity ...................................................................................... 106
7. Conclusion and Outlook ............................................................................................................. 107
References ...................................................................................................................................... 109
Appendices .................................................................................................................................... 120
1. Introduction

1.1. About Nanofluids

Heat transfer plays major role in many fields of industry; such as, transportation, air conditioning, power generation, electronic, etc. Moreover, high-performance cooling is widely needed in industrial technologies. Due to this fact, various studies and researches are aimed to increase cooling performance of working fluids.

Nanofluids, defined as suspended nanoparticles with the size of 1 to 100 nm inside fluids, have drawn vast attention due to recently claimed high performance in heat transfer in the literature. In heat transfer, one of the major parameters is thermal conductivity of working fluid. Currently, most prevailing fluids utilized for cooling are water, ethylene glycol and engine oil which have much lower thermal conductivity compared to lots of solids including metallic ones; such as silver, copper and iron or non-metallic materials; like alumina, CuO, SiC and carbon nanotubes (CNTs). This fact was starting point of an idea, which was creating mixture of solid and fluid in order to improve thermal conductivity of fluid and to have better heat transfer performance consequently [1].

Maxwell was the first one who initiated the use of small-sized solid particles inside fluids to increase thermal conductivity. His idea was based on suspension of micro- or milli-sized solid particles inside the fluids on that time [2]. However, large size of particles in scale of milli- or even micro-sized particles causes several technical problems [3] which can be listed as below:

- Faster settling time
- Clogging micro-channels of devices
- Abrasion of the surface
- Erosion of pipelines
- Increasing pressure drop

For the first time, Choi et al. [4] at Argonne National Laboratory in the USA coined the term nanofluids for fluids with suspended nanoparticles inside. Nanofluids are defined as colloidal suspension of solid particles with the size of less than 100 nm and the solid particles concentration of lower than 5 vol%.

The importance of nano-sized particles and their benefits compared to microparticles has been investigated and it could be stated that nanoparticles possess [5]:

- Longer suspension time (More stable)
- Much higher surface area
- Larger surface area/volume ratio (1000 times larger)
- Higher thermal conductivity
- Lower erosion and clogging
- Lower demand for pumping power
- Reduction in inventory of heat transfer fluid
- Significant energy saving

Higher performance of heat transfer, in both conduction and convection heat transfer modes, was reported by several researchers, afterward. Increment in thermal conductivity of fluid was one of the first features investigated by Eastman et al [27]. They observed 40% increment of thermal conductivity after adding 0.3 vol% of copper nanoparticles into ethylene glycol [27]. Moreover, convection heat transfer of
nanofluids was also investigated by different researchers and based on that, significant improvement was reported in heat transfer rate. Buongiorno considered seven possible mechanisms of fluid particle slip during the convection of nanofluids [6]. Heris et al. examined laminar flow convective heat transfer through circular tube with constant wall temperature boundary condition. The experiments were performed for a wide range of (650–2050) Reynolds number and for various concentrations [7].

Observing enormous thermal conductivity increment, Das et al. have conducted experiments on pool boiling heat transfer. Pool boiling of Al₂O₃/water nanofluid in horizontal tube was tested and they concluded that extremely low concentration of small nanoparticle will dramatically increase the critical heat flux (CHF) in a pool boiling system [8, 9].

From heat transport point of view, various results with great disparities have been reported in recent years. For instance, it has been claimed that improving thermal transport properties of nanofluids would have several advantages and the most important ones was summarized as below [10]:

- Improvement of the efficiency of heat exchanging
- Reducing size of the system
- Providing much greater safety margins
- Reducing costs

It is important to note that synthesis and preparation phase of nanofluids would play major role, since better preparation results in better performance of nanofluids and improves thermal transport properties. Currently, most efforts are pushed to increase thermal conductivity while other thermal transport properties such as viscosity and heat capacity, have been paid less attention to [10].

Moreover, many mechanism and models were suggested by different researches regarding thermal conductivity properties of nanofluids. Maxwell and Hamilton-Crosser (HC) initiated making a model from the behavior of colloidal suspension systems with micrometer or larger-sized particles. However, they have only considered volume fraction and geometry of particles as effective parameters in thermal conductivity [2, 32]. In recent years, predicting behavior and making models have improved interestingly for nanofluids, considering different effective parameters on thermal conductivity of nanofluids. Yet, many activities are focused on improving Maxwell’s model.

### 1.2. Preparation of Nanofluids

It was expressed that nanofluids would be prepared by suspending solid particles with the size of less than 100 nanometers inside a basefluid. Terms “synthesis” and “Characterization” are widely used in literature, describing preparation phase of nanofluids. In general terms, it could be stated that nanofluids include nanometer sized solid particles, fibers, rods or tubes suspended in different basefluids [11].

Together with basefluids and nanoparticles, additives are utilized to increase stability of nanofluids and to improve dispersion behavior of them. More common nanoparticles and basefluids exploited in synthesis would be tabulated as below [12]:
In general, two production methods of preparation and dispersion, called one- and two-step method, exist. Moreover, the key to significant increment of thermal conductivity of nanofluids is synthesis, within which non-agglomerated nanoparticle are suspended in basefluid [5].

In the single-step method, preparing nanoparticles and dispersing inside basefluid occurs simultaneously. In two-step method, nanoparticles are processed and made by some techniques first and then dispersed them into basefluid. Most nanofluids including oxide nanoparticles are produced by means of the two-step method, but for metallic nanoparticles or particles with high thermal conductivity one-step method is preferred [5]. For instance, Hong prepared Fe/ethylene glycol nanofluid by taking advantage of the two-step method [28 , 49]. In this case, synthesis of Fe nanoparticles have been performed by chemical vapor condensation process and then, it was dispersed in basefluid.

1.3. Objective of present research

KTH is a part of the World’s largest collaborative project for the research and development of nanofluid coolants, NanoHex comprises of a consortium of 12 leading European companies and research centers. Two departments of KTH are involved in NanoHex project for preparation of nanofluids as well as measurement of their thermophysical properties. This research is focused on three properties of nanofluids, which are highly significant; including thermal conductivity, viscosity and stability.

As it was mentioned, enhancement of thermal conductivity of fluids, by adding nanoparticles inside and improving thermal transport properties, are reported by different researches. Any new sample made by project partners was anticipated to have noticeable increment of thermal conductivity. In order that,
measurement of thermal conductivity of new samples as well as basefluids in the same environmental conditions have been accomplished. Afterwards, obtained result has been compared in different ways.

There are many methods in literature measuring thermal conductivity. Transient Plane Source (TPS) method, which was applied in this study, is a method for measuring thermal conductivity of different materials.

Rheological behavior of nanofluids, besides thermophysical properties, is an important issue. Although addition of nanoparticles to the basefluids may increase the thermal conductivity and alter thermal properties, it will also affect the viscosity of nanofluids. The viscosity is very critical factor in industry from economical point of view. This issue is directly associated with pumping power to share the nanofluid inside the cooling system. Since there was less focus on viscosity of nanofluids other than thermal conductivity, there was a need to consider viscosity to have a commercial view for these cooling media. There was some increase in thermal conductivity reported in the KTH Lab and by other partners in the project (NanoHex). Thus, the viscosity evaluation by measuring both basefluid and nanofluids could show how applicable these nanofluids are. There are several methods to measure the viscosity of fluids. A rotating coaxial viscometer chose to measure the viscosity of nanofluids. The advantage of this method, which was done using DV-II + Pro from Brookfield Engineering Company, is fast measurement and versatility.

Moreover, the stability of nanofluid, which is bilaterally associated with the thermal conductivity and viscosity, can be a critical parameter to evaluate the nanofluids. Stability of nanofluids refers to stability of nanoparticles inside the basefluid. The longer time that nanoparticles are floating inside the fluid, the better thermal properties is expected from nanofluid. Therefore, among different method of measurement sedimentation balance was chosen and an instrument was designed to measure.
2. Literature Review

Respecting objectives of the study, three general topics were chosen to be investigated which are:

- Thermal Conductivity
- Viscosity
- Stability

For any particular topic, literature review has been done separately investigating effective parameters and common measurement methods.

2.1. Thermal Conductivity in Literature

In this section, most important effective parameters on thermal conductivity of nanofluids together with more common measurement methods has been extracted by reviewing literatures.

2.1.1. Effective parameters on thermal conductivity

Literature states different features influencing thermal conductivity of nanofluids. Based on literature, some parameters influence on thermal conductivity of nanofluids with no doubt such as size, temperature, concentration, particle motions and so on. In this section, some of these parameters have been reviewed.

Nanoparticle can be considered as the key element of nanofluid, which plays major role in this case. Situation of nanoparticles either during synthesis or after that can be highly effective on different thermophysical properties of it; such as thermal conductivity or viscosity. Following are most important features affecting thermal conductivity.

2.1.1.1 Morphology

In material science, morphology would be defined as study of shape, size, texture and phase distribution of physical objects [16]. Regarding this type of study of nanoparticles, the effect of size of nanoparticles has been investigated by some researchers such as Chon et. al who have declared strong effect of nanoparticle size on thermal conductivity of nanofluid [17]. Furthermore, Chopkar et. al. have had studies on ethylene glycol based nanofluids containing Al$_{70}$Cu$_{30}$ nanoparticle and discovered that thermal conductivity strongly depends on the size of nanoparticles [18]. In 2009, Minsta et al. tested two different sizes of Al$_2$O$_3$ nanoparticles that were 36 and 47 nm. Regarding the results of their experiments, nanofluids with smaller nanoparticles showed higher enhancement in thermal conductivity [48].

The first researchers who have reported effects of shape of nanoparticle, including spherical or cylindrical, on the enhancement of thermal conductivity of SiC nanofluid were Xie et al. [19]. Later on, Murshed et al. investigated the effects of particle shape on thermal conductivity of nanofluids. Investigation was carried out on spherical and rod-shaped TiO$_2$ nanoparticles with diameter of 15 nm and 10 nm respectively and length of rod-shaped nanoparticles were 40 nm. Finally, they reported higher thermal conductivity of rod-shaped nanoparticles [20]. In addition, Liu et al. carried out some tests on Cu nanoparticles with the size of 50 to 250 nm and shape of needle and square dispersed in water to investigate the effect of these two parameters on thermal conductivity [21].

Other characteristic of nanoparticle is specific surface area (SSA), which is supposed to be taken into account by researchers during preparation since it is effective on thermal conductivity of nanofluid and can be defined as follow:
As it can be seen in the equation, decreasing particle volume and increasing particle surface area will increase SSA and as a result, thermal conductivity will be increased due to more contact surface. Xie et al. specifically showed in their research that increasing SSA leads to enhancement of thermal conductivity [22]. It should be noted that all mentioned features in morphology should be considered in preparation phase precisely.

### 2.1.1.2 Temperature

During thermal conductivity measurement of nanofluids, it has been discovered that it is strongly depends on temperature. Das et. al. have done their research on water-based nanofluids including CuO and Al₂O₃ in the range of 20 to 50 °C. They stated temperature-dependency of nanofluids and elaborated that it is most probably the effect of motions i.e. when particles have more motions inside the basefluid with higher temperatures, thermal conductivity of the nanofluid will be increased [23]. In 2006, Ding et al. had some studies on CNT-water nanofluids and they showed that thermal conductivity is highly depends on temperature [24].

In recent researches, it has been approved that temperature and thermal conductivity have direct relationship which means when temperature increases, thermal conductivity of nanofluid rises as well. Recently, Yu et al. have investigated aluminum nitride nanofluid and confirmed this fact [25].

### 2.1.1.3 Concentration

The other key issue that can highly affect thermal conductivity of nanofluid is concentration of nanoparticles inside the basefluid. In different reports, concentration has been stated in both types including volume as well as weight percentage. Choi et al. and Eastman et al. performed researches on CNT’s and showed nonlinear relationship between nanofluid concentration and thermal conductivity [26, 27]. In addition, nonlinear relationship of these two properties, i.e. thermal conductivity and concentration has been investigated within studies accomplished by Hong et al. with Fe–ethylene glycol nanofluids [28]. Nowadays, it has been proved by different models and experiments that thermal conductivity and concentration of nanoparticles have nonlinear and direct relationship, i.e. increment in one of them results in increment in the other one. Research done by Yu et al. can be mentioned as one of them [29]. They have studied and compared experimental and modeled results for thermal conductivity versus various volume concentrations of ethylene glycol based ZnO nanofluid [30]. Duangthongsuk and Wongwises were other researchers who investigated the effect of volume fraction of nanoparticles on thermal conductivity. Their study was evaluating thermal conductivity change in different volume fractions of particle from 0.2% to 2% of TiO₂-water based nanofluid in temperature of 25 °C [31]. Furthermore, they have compared results of their experiments with H-C model [32], Bruggeman model [33], Wasp model [34] Yu and Choi model [35], Effective medium theory [36] and illustrated that test results follow mentioned models well.

### 2.1.1.4 Motion

First who discussed and raised topics regarding the role of motion as a mechanism behind enhanced thermal transport in nanofluids were Wang et al. [37]. Three types of motion have been vastly discussed in literatures namely:

- Thermophoretic motion (Motion caused by temperature gradient)
Brownian motion (force)
Osmophoretic motion (Motion in concentration gradient)

When Das et al. discovered the fact that nanofluids have temperature-dependent thermal conductivity, they posed motion of particles as important reason for that [23]. Afterwards, motion of particles caused by temperature gradient, which is called Thermophoretic motion, has been investigated more by Koo et al. [38].

However, most effective type of motion which has been investigated by different researchers and has stated as very effective reason in increasing thermal conductivity of nanofluids is called Brownian motion. In 2002, Keblinski et al. declared four possible microscopic mechanisms for the increase in the thermal conductivity of nanofluids among which Brownian motion was the reason of increasing [39]. They explored particle-particle collision as the effect of Brownian motion which causes heat transfer increment eventually. Afterwards, Xuan et al. took the effect of Brownian motion into account, while developing a dynamic model for the first time [40] and it has been considered as an issue later on by others [41-43]. Moreover, Jang and Choi expressed that Brownian motion of particles can induce nanoscale convection which enhances thermal conductivity of nanofluids [41].

Third type of motion is called osmophoretic motion which can be defined as motion in concentration gradient and vary by concentration of particles. Koo et al. discovered that this type of motion as well as thermophoretic one cannot play as major role as Brownian motion in mechanism of thermal conductivity increment of nanofluids, and based on this, most of the focus is directed toward Brownian motion [44].

2.1.1.5 Thermal conductivity of nanoparticles

Inside one specific basefluid, thermal conductivity of particles would greatly influence on thermal conductivity of one sample comparing the other one while both possess same basefluid. In this case, higher thermal conductivity of particles is expected to lead in higher thermal conductivity of nanofluid. This fact has been proved by different researches and experiments. One of them is what Li and Peterson have done. They have tested two water-based nanofluids in which CuO and Al₂O₃ were suspended. Based on their idea since CuO solid particles show higher thermal conductivity than Al₂O₃, the same scenario is true for nanofluids containing these two types of particles. Their experiments were accomplished under same conditions for both samples and they were containing the same volume fraction of particles as well [45].

Chopkar et al. studied effect of particles materials in 2008 as well. They dispersed Al₂Cu and Ag₂Al inside mixture of water and ethylene glycol. Since thermal conductivity of Ag₂Al is higher than Al₂Cu, nanofluids containing them show similar behavior that particles do [46].

2.1.1.6 Thermal conductivity of basefluid

As it was mentioned earlier, motion of particles especially Brownian motion can affect thermal conductivity of nanofluids. One noticeable parameter, which is in direct relationship with motion of particles, is viscosity of basefluid [40]. Effect of electric double layer around nanoparticles could be considered as one influential parameter on thermal conductivity of nanofluids, depending on basefluid. This fact was examined and showed by Lee [47].

In 1999, Wang et al. tested several nanofluids containing Al₂O₃ and CuO as nanoparticles and water, ethylene glycol, vacuum pump fluid, and engine oil as basefluids. Their experiments revealed that the highest thermal conductivity ratio (thermal conductivity of nanofluid divided by the thermal conductivity of base fluid) belongs to the combination of Al₂O₃ and ethylene glycol [37].
Xie et al. were other researchers who have investigated the effect of different base fluid on thermal conductivity of nanofluids. Deionized water, glycerol, ethylene glycol, pump oil, ethylene glycol–water and glycerol–water mixtures with different volume fractions were utilized as base fluids in their tests [22].

### 2.1.1.7 Clustering

Other feature affecting thermal conductivity of nanofluids, which always can be taken into account, is clustering. Keblinski et al. posed nanoparticles clustering as one of four effective parameters on thermal conductivity of nanofluids [39]. Years later, Hong et al. studied effect of this phenomenon on Fe nanoparticles suspending in ethylene glycol. Investigating effect of ultrasonic vibration from 0 to 70 min, Fe/ethylene glycol nanofluid has formed different sizes of clusters which have affected the thermal conductivity of nanofluid interestingly [49]. Zhu et al. also stated that clustering and nanoparticle alignment was responsible for the thermal conductivity increment after testing Fe$_3$O$_4$/water nanofluid [50]. Moreover, Evans et al. also investigated effect of clustering on thermal conductivity of the nanofluids [51]. It is interesting to note that in different models presented by different researches, regarding thermal conductivity of nanofluids, the effect of clustering has been regarded by some researchers such as Xuan et al. [40].

### 2.1.1.8 Acidity (pH)

Literature survey reveals that there are not a lot of researches investigating impact of pH of basefluid on thermal conductivity of nanofluid. However, Xie et al. were first who have investigated this issue and noted that increasing pH value results in decreasing thermal conductivity ratio after doing some tests on Al$_2$O$_3$/water nanofluid. In more detailed description, they reported that thermal conductivity increment of Al$_2$O$_3$/water nanofluid varies from 23% to 19% when pH changes from 2 to 11.5 [22]. In addition, Lee et al. also stated strongly pH-dependency of nanofluid thermal conductivity [52].

Furthermore, Wang et al. investigated the effect of pH on thermal conductivity of nanofluids. Eventually, they achieved optimum pH in which highest value for thermal conductivity comes up. Concerning their results, pH of about 8 for Al$_2$O$_3$/water and about 9.5 for Cu/water led to maximum thermal conductivity enhancement. They also discovered that thermal conductivity of base fluid, which has been mentioned as one significant issue affecting thermal conductivity of nanofluid, does not strongly depend on its pH value [53].

Another study investigating effect of pH on thermal conductivity was performed by Murshed et al. They reported that increment in pH value causes reduction of thermal conductivity. They have tested thermal conductivity of TiO$_2$ inside water nanofluid while it should be pointed out that they observed only 2% reduction when pH was changed from 3.4 to 9 [54].

### 2.1.1.9 Additives

Additives are utilized to keep nanoparticles in suspension and prevent them from agglomeration. Thus, they are expected to cause thermal conductivity enhancement of nanofluids. Eastman et al. have executed some tests on Cu in ethylene glycol with and without additive, which was thioglycolic acid in this case. Finally, they presented that additive can strongly increase effective thermal conductivity of nanofluid [27].

Different types of additive have been investigated by Assael et al. on MWCNT (Multiwall Carbon Nanotube) in water. They added CTAB and Nanosperse AQ to MWCNT and observed higher thermal conductivity ratio of MWCNT containing Nanosperse AQ as additive [55].

Finally, it should be indicated that although there are not a lot of researches in this area, most of present cases indicate enhancement thermal conductivity ratio [56].
All in all, it should be noted that lack of confirmed reliable information regarding thermal conductivity of nanofluids and the real mechanism behind the augmentation, act as great hindrance for their commercial exploitation [57].
2.1.2. Measurement techniques for thermal conductivity

Nanofluids attracted a vast attention due to increment in thermal conductivity compared to basefluid. Measuring these thermophysical properties was a challenge for a long time since different methods and techniques presented different results. Thus, the method which is going to be used would be significant to lower the measurement error and uncertainty as much as possible.

In this section, major thermal conductivity measurement methods from different literatures have been described briefly, and following are methods which are going to be investigated [57]:

- Transient hot-wire techniques
- Thermal constants analyzer techniques
- Steady-state parallel-plate method
- Cylindrical cell method
- Temperature oscillation technique
- 3ω method
- Thermal comparator method

Generally, Fourier’s law for conduction heat transfer can be utilized to measure thermal conductivity of a material. Temperature difference can cause heat transfer through materials which is known as conduction heat transfer. Thermal conductivity is particular properties of the material which can differ from one material to another and can be calculated as follow:

\[
k = \frac{q/A}{\Delta T/L}
\] (2.2)

Where \(k\) is thermal conductivity, \(q\) is magnitude of heat transmission, \(\Delta T\) is temperature difference, \(A\) is cross sectional area and \(L\) is the length. To simplifying calculations, one-dimensional temperature filed and steady state flow would be considered.

In Case of liquids, avoiding convection should be regarded during measurements and since fluids does not have definite shape, size and cross sectional area, it would be more difficult to calculate thermal conductivity. Thus, measurement should take place in a very short time. Even the situation is worse in case of nanofluids, whereas suspended nanoparticles may cause a major problem [57].

Paul et al. presented a report reviewing different methods of measuring thermal conductivity and based on that, Transient hot-wire method has been introduced as most popular method using by scientists and researchers. Figure 2.1 depicts portion of different methods in literatures [57]:
2.1.2.1. Transient hot-wire (THW) method

This can be known as the most regular and the oldest method of measuring thermal conductivity. Comparing other methods, it can be known as a very fast measurement method and conceptual design of the apparatus is simple as well. It has been used to measure thermal conductivity of powders at the beginning. However, it has been improved by many researchers. Inasmuch as the potential of method to lower possibility of natural convection, it is applied to measure thermal conductivity of fluids [57].
Transient hot-wire experimental setup is composed of Whetstone bridge circuit, DC power supply, stabilizer, switch, A/D converter and a computer (Figure 2.2). In this method, a platinum wire is used for both heating and measuring temperature. Constant power is supplied to the wire causing temperature increment of that [57]. Consequently, wire would heat up the temperature of material which can be solid, liquid or nanofluid. Afterwards, thermal conductivity of the sample can be calculated concerning heat flux, temperature difference, and some geometric parameters based on Fourier’s law.

Thermal conductivity of nanofluids has been measured by several researchers using transient hot-wire method [20, 36, 58, 59]. It is worth mentioning that transient hot-wire method has been developed over the years and some variations of that so called liquid metal transient hot-wire technique and transient short hot-wire have been applied to measure thermal conductivity of liquids [57].

The liquid metal transient hot-wire technique is used to measure thermal conductivity of electrical conducting liquids [60] whilst transient short hot-wire is a suitable method for measuring thermal conductivity of corrosive liquids [61].

2.1.2.2. Transient Plane Source (TPS) method

To compute thermal conductivity, transient plane source (TPS) theory is utilized by thermal constant analyzer. TPS sensor plays similar role as what probe or wire does in THW method; which means it acts as heating source together with temperature sensor. Following are advantages mentioned for this method in literature:

- Fast measurement
- Capability of measuring samples having wide range of thermal conductivity (From 0.02 to 200 W/mK)
- No sample preparation is required
- Sample size can be flexible [62]

Main components of experimental setup for transient plane source method are thermal bath with thermometer, TPS sensor, sample holder, thermal constants analyzer and computer. For calculating thermal conductivity of solids, probe of the analyzer is sandwiched between two sections of the material while for liquids it is immersed into the sample. The sample holder would be kept inside thermal bath with constant temperature and small amount of power will be supplied in short time to the sensor. Analyzer can calculate thermal conductivity later on.

It should be pointed out that convection can cause error in the result of thermal conductivity, thus parameters of analyzer should be controlled properly. This method has been used by some researchers such as Zhu et al. [62] and Jiang et al. [63].

2.1.2.3. Steady-state parallel-plate method

Challoner and Powel [64] described and used a guarded hot-plate design which is the basis of constructing an apparatus using steady-state parallel-plate method for measuring thermal conductivity. In this apparatus, small volume of fluid sample is located between two parallel round pure copper plates. Cross-sectional area and total area of the plate are determined. Sample holder is located in a larger cell made of aluminum. Two thermocouples are installed in top and bottom of the sample holder measuring temperature difference of the sample. Heater is used to apply warm up the sample as well. Moreover, heat conduction equation extracted from Fourier’s law is applied to calculate thermal conductivity. Wang et al. used the method to measure thermal conductivity of Al₂O₃ and CuO, dispersed in water, vacuum pump fluid, engine oil, and ethylene glycol [37].
2.1.2.4. Cylindrical cell method

It might be known as one of the most common steady-state methods used for measuring thermal conductivity of fluids [57].

Kurt et al. utilized cylindrical cell method to measure thermal conductivity of water and ethylene glycol and compare the results with outcomes of artificial neural networks (ANNs) predictions [65]. The instrument applying cylindrical cell method is composed of two coaxial cylinders which can be named as inner and outer cylinders. Inside the inner cylinder (made of copper), heater is placed while inside the outer cylinder (made of galvanize) where there is a gap between outer and inner cylinder, fluid sample would be kept. Two thermocouples are utilized to measure temperature difference after applying power and heat transform caused by heater. Using Fourier’s law in coaxial cylinders, thermal conductivity of sample in the gap could be computed.

2.1.2.5. Temperature Oscillation method

Temperature oscillation method uses oscillation method proposed by Roetzel et al. [66] For the first time, measures temperature response of the sample when a temperature response or heat flux is imposed [57].

![Figure 2.3: Schematic of transient temperature oscillation technique](image)

Regarding experimental setup (Figure 2.3), main 7 components for using temperature oscillation method are a test cell, cooling water, Thermal bath, DC power supply, amplifier and filter, data acquisition system and computer. A brief description of the device is as follow. Sample which is hold inside test cell would be heated up by means of supplying power from DC power supply. Thermocouples measure temperature variations of the sample continuously and at the same time cooling water from bath is trying to avoid temperature excess from preferred value or set point. Displaying temperature value on line would provide assessment of steady oscillation and recording data. Thermocouples data are amplified through amplifier with filter.
By this method, thermal diffusivity of the sample can be measured accurately. By means of that, thermal conductivity can be calculated having density and specific heat from handbook.

2.1.2.6. $3\omega$ method

Similar to THW, $3\omega$ is utilizing an element acting as heater and thermometer possessing radial flow of heat. However, the major difference between transient hot-wire and $3\omega$ method is that in the former time dependent response is used while in the latter temperature oscillation is applied. Passing sinusoidal current at frequency of $\omega$ through metal wire, heat wave at the frequency $2\omega$ would be created. Afterwards, voltage components at the frequency $3\omega$ would be reduced [57]. Oh et al. were researchers who used this method measuring thermal conductivity of $\text{Al}_2\text{O}_3$/DI and $\text{Al}_2\text{O}_3$/ethylene glycol nanofluids [67].

2.1.2.7. Thermal comparator method

Powel et al. posed the idea of thermal comparator in which two metal balls are located in block of a thermal insulation in parallel to measure thermal conductivity of materials such as aluminum, iron, alloy steel and so forth [68]. Afterwards, the method has been used to measure thermal conductivity of different materials by other researchers [69, 70, 71].

Through the years, idea was developed by some researchers until Paul et al. developed the idea inherently to measure thermal conductivity of nanofluids [57]. Mainly, new device is composed of a copper probe, sample holder, DC voltmeter, voltage stabilizer and a heater. It is interested to note that unlike some other mentioned methods, in this technique probe is required to have only a point contact with the sample.

Thermocouple is placed between the sample and the probe which is supposed to have constant temperature by heater. Direct relationship should exist between thermal conductivity and observed differential emf after sensing temperature by thermocouple. It occurs when probe would be kept in point contact with the sample and thermo-emf is generated in circuit to cover the probe assembly and nanofluid. Considering different voltages in the circuit as well as boundary conditions and proper equations, thermal conductivity can be calculated [57]. Paul et al. reported it as a reliable method when they tested some samples such as water and ethylene glycol.
2.2. Viscosity of Nanofluids

2.2.1. Effective parameters on viscosity:

Since the conventional base fluid such as water, EG, DEG, AFN, Oil, etc. have been used in different applications such as power plants, heating/cooling applications, chemical industry, automation, and so forth. However, they have not shown proper thermal properties, which impose higher cost to the system [72].

In the past decades, the investigation of nanofluids viscosities was not considered as same as thermal properties. Yet, viscosity of nanofluid is one of the most critical parameters in nanofluids, which should be considered by researchers and need to be investigated thoroughly. The key point in a nanofluid is to compromise the Thermal conductivity and Viscosity because the viscosity increment offsets thermal conductivity increase [73-75].

In order to design a proper cooling system, it is expected that nanofluids as cooling media have almost considerable increment in thermal conductivity. On the other hand, almost less increment or constant viscosity is expected which means higher ratio of thermal conductivity and viscosity. There are different crucial parameters influencing the viscosity that are investigated by researchers. These factors consist of temperature, volume concentration, particle size, morphology, time sonication, shear rate, etc [12].

Given papers reviewed, it is tried to list different factors which can influence the viscosity.

- Temperature
- Volume fraction
- Morphology
- Shear rate
- Dispersion method, stabilizers and Clustering

2.2.1.1. Temperature

Temperature is discussed in literature as one of most important parameters affecting the viscosity. Prasher et al. [76] have shown that the relative viscosity of nanofluids is not a strong function of temperature while Li et al. [77] have proven a decrement of apparent viscosity by increasing the temperature. Nguyen et al. [72] measured some water-based nanofluids (Al$_2$O$_3$ and CuO) with different particle size including 29, 36 and 47 nm. The results showed a dependency of viscosity to the temperature. Ding et al. [24] experimentally proved that the CNT viscosity in different volume concentration decreases by temperature. L. Chen et al. [78] investigated the multi walled carbon nano tubes (MWCNTs) in distilled water. They showed there is almost no change in viscosity of nanofluid with increase of temperature up to 55°C. Surprisingly, sudden increment of viscosity happened in range of 55 to 70°C. On the other hand, Lee et al. [79] in 2010 measured SiC and observed that the viscosity of SiC decreases by temperature. There are some other contradictory reports where Chen et al. [87, 88] have found the viscosity as a strong temperature dependent phenomenon, yet, Prasher et al. [76] and L. Chen et al. [78] presented viscosity as a temperature independent phenomenon.

Anoop et al. [80] measured Al$_2$O$_3$, CuO (ethylene glycol based) and Al$_2$O$_3$ (water-based) nanofluids in different volume concentrations of 0.5, 1, 2, 4 and 6%. The temperature range set between 20 and 50 °C.
and a reduction of viscosity with temperature was observed. Duangthongsuk et al. [31] chose TiO$_2$ in temperature range of 15-50 °C in which similar result as Anoop et al. [80] was achieved.

Turgut et al. [81] also selected TiO$_2$ / deionized water to investigate influence of temperature (13-55 °C) on viscosity and thermal conductivity, results proved a reduction of viscosity by temperature.

Kole and Dey [82] who worked on nanofluid as a coolant in an ICE, concluded that the alumina based nanofluid (up to 1.5 vol%) viscosity in temperature range of 10 to 50 get lower in higher temperatures.

Pastoriza-Gallego et al. [83] measured water-based CuO in temperatures of 283.15–323.15 K, with a step of 10 K and pressure range from 1 to 45 MPa. In their experiments, they observed a reduction behavior for nanofluid by increasing the temperature (wt% of CuO was between 1-10).

Namburu et al. [84] investigated the viscosity of Water and ethylene glycol based nanofluid (SiO$_2$) in which non-Newtonian behavior (exponential) observed in the range 35°C to 50°C. In another investigation [85] they found something different that the mixture of CuO by Water and ethylene glycol shows Newtonian behavior in the same temperature range. In both research viscosity reduction by temperature is proved. Naik et al. [86] also found viscosity of CuO/PG–water nanofluids decreases exponentially by temperature for a range of 258 to 335 K.

2.2.1.2. Volume fraction

Volume concentration of nanofluids is another important characteristic of these coolant media which directly influences the viscosity of nanofluids, on the other hand, it affects the thermal properties. There have been many researches to see the effect of wt% of nanoparticles on viscosity. The result almost shows the higher wt% is, the more viscosity nanofluid has. Thus, the tradeoff between thermal properties and rheological properties is an essential issue to consider. Concerning the Prasher et al. and Li et al [76, 77] experiments, the volume concentration can highly affects the viscosity of nanofluids. Lee et al. [79] investigating on volume concentration found that the viscosity increases by versus volume fraction. Ding et al. [24] also mentioned that the viscosity of nanofluids increased with increasing CNT concentration. L. Chen et al. [78] found the increment of volume concentration is led to higher viscosity for MWCNTs (they measured volume fractions of 0.002, 0.004, 0.006, 0.008 and 0.010). Das et al. [8] measured Al$_2$O$_3$ and found that viscosity is higher for nanofluids with stronger particle concentration. Besides, they believed that there is a firm dependency of volume concentration and non Newtonian behavior of nanofluids.

Murshed et al. [82] considered the effect of volume concentration for Al$_2$O$_3$ and TiO$_2$ in deionized water and concluded 82% and 86% increment, respectively. L. Chen et al. [78] as other researchers showed rising of the viscosity in accordance with nanoparticle loading for MWCNTs. He et al.[89] has also measured TiO$_2$ in distilled water and stated the volume concentration rises the viscosity of nanofluids. Yet, Chevalier et al [90], Pastoriza-Gallego et al. [83] and Namburu et al. [84] expressed a contradictory result that the viscosity decreases by increasing the volume concentration.

2.2.1.3. Morphology

Transmission electron microscopy is base of morphology and properties of the nanoparticle and nanofluids [24]. Morphology of nanoparticles, both shape and size, can affect on viscosity and pumping power of the cooling system. Therefore, an investigation on nanoparticles morphology would direct the nanofluids towards more effective and economical cooling media. Prasher et al. [76] also expressed that the nanoparticles diameter may not contribute to changing the viscosity highly. However, Nguyen et al. [72], who considered 29 nm (CuO), 36 and 47 nm (Al$_2$O$_3$) on
nanoparticles size, experimentally proved that the 47 nm of Aluminum oxide has a higher viscosity that 36 nm-the volume concentration of higher than 4%.

He et al.[89] reported an increment of shear viscosity by increasing the particle size. For three different nanoparticles sizes (95, 145, 210 nm) they measured water-based TiO₂ in different volume fraction. Evans et al. [51] measured nanofluid containing fiber and spherical shaped nanoparticles and found both higher thermal conductivity and viscosity for nanofluid with fiber shaped nanoparticles—there is higher possibility of clustering and viscosity increment.

Lu and Fan [91] had both theoretically and experimentally investigation on particle size. They studied water and ethylene glycol based Al₂O₃ and found that while particle size increases the viscosity decreases. Besides, they mentioned that the change in shear viscosity is less for nanofluids containing particles with diameters higher than 30 nm. Anoop et al. [91] also studied similar result for Al₂O₃ in different volume concentration (2 wt%, 4 wt% and 8 wt%). They proved that nanofluid containing nanoparticles with diameter of 45 nm have higher viscosity than nanofluid containing 150 nm.

Chevalier et al. [90] measured SiO₂/water and SiO₂/EG including nanoparticles with 35, 94, 190 nm diameter and found an increment of viscosity with decrease of nanoparticle size. Namburu et al.[84] also measured SiO₂ based nanofluids with three nanoparticle size (20, 50 and 100 nm) and proved the previous result by Chevalier et al.[90] Pastoriza-Gallego et al. who studies CuO in water with two different nanoparticle size (27 and 37 nm) in which they exhibited lower viscosity for nanofluid with larger nanoparticle size. Prasher et al. [76], on the other hand, have expressed that viscosity is independent of particle size. They studied Al₂O₃ with 27, 40 and 50 nm particle size with propylene glycol and did not see any considerable change in viscosity regarding particle size.

Concerning particle shape, there are a limited number of researches where the viscosity introduced strong function of nanoparticle shape [93, 94]. Timofeeva et al. [93] studied that elongate particles like platelets and cylinders have larger viscosity compared the other shape at the same volume fraction.

2.2.1.4. Shear rate

Shear rate is another parameter which can affect the viscosity in non-Newtonian nanofluids. Ding et al. [24] worked by CNTs found shear thinning phenomenon in nanofluids. It means nanofluids can sometimes show more appropriate fluid flow performance because of shear thinning which happens at higher shear rates. Shear viscosity of nanofluids, which can be especially altered in non-Newtonian nanofluids, tested by Chen et al [87] using titania ethylene glycol based. They showed Newtonian behavior and proved that shear viscosity depends on both Temperature and particle’s concentration.

Moreover, Prasher et al. [76] reported that the viscosity of alumina-based nanofluid are independent of shear rate providing that the nanofluid shows a Newtonian behavior.

Das et al. [8] and Putra et al. [95] measured water-based Al₂O₃ and CuO in different shear rates. They observed Newtonian behavior for these nanofluids in volume concentration range of 1% to 4%.

Yu et al. [25] studied the effect of shear rate in temperature range of 10 to 60 °C on viscosity. They found that the shear thinning phenomenon (non Newtonian behavior) happens at higher volume concentration that 5%-the vol% less than 5 showed Newtonian behavior.

2.2.1.5. Dispersion method, stabilizers

Wang et al. [37] made a dispersion method and its contribution to viscosity. They analyzed three different methods of dispersion and measured dianoized water-based Al₂O₃ with 5 vol% and particle size of 28
nm. They reported a 86% increment in viscosity for this nanofluid. The dispersion method that they used was a mechanical blending technique (method 1). Besides, coating particles with polymers (method 2) and filtration (method 3) were applied for dispersion of nanoparticles.

40% increment is showed for ethylene glycol based $\text{Al}_2\text{O}_3$ at a volumetric loading of 3.5 vol% by them. In general their results demonstrate a dependency of viscosity on dispersion method and first method contributes to viscosity increment compared to two other ones.

Pak and Cho [96] measured water-based $\text{Al}_2\text{O}_3$ with 13 nm particle size and $\text{TiO}_2$ with 27 nm particle size. There was found a high discrepancy of viscosity between base fluid and nanofluid. They tried to adjust the PH value and apply repulsion technique so as to disperse nanoparticles. As a result, the dependency of dispersion method again showed its role in viscosity increment.

Wena et al. [97] in order to overcome stability issue in nanofluids, stabilizers are introduced which are added to the nanofluids in three different steps; firstly preparing pure liquid, secondly mixing suitable stabilizers to the pure liquid (base fluid) and finally dispersing nanoparticles into the base liquid. This group believes that the stabilizers which are important factors should be considered in viscosity of nanofluids.

Moreover, other parameters such as PH and Sonication time can affect the viscosity of nanofluids.

2.2.2. Viscosity Measurement Methods:

There are generally a limited number of literatures which worked on the viscosity instrumentation measurement. Viscosity is one of critical issues in fluids and tightly contributes to costs in industry.

Buiochi et al. [98], Curtin et al. [99], Zafarani-Moattar [100] and Khoshsima and Zhang et al. [101] mentioned high importance of viscosity using different instrumentations.

Methods which are frequently used in nanofluids viscosity measurements are divided into two groups as flow type and drag type [102].

2.2.2.1. Flow Type Viscometers:

Flow type method is composed of two main methods, namely capillary and orifice method.

2.2.2.1.1. Capillary Viscometers

This method is introduced as the best method for fluid viscosity measurement. Capillary viscometers are basically used for Newtonian, incompressible and wall adherence liquids [103]. The principle of capillary viscometers is the time at which a standard volume of fluid passes through a length of capillary tube. The pre-condition assumed for this measurement is having a laminar, incompressible and stationary fluid. Moreover, since flow influence at the entry and exit of capillary is negligible, the viscosity of fluids is considered to be pressure independent.

Capillary viscometers are working based on Hagen-Poiseuille Law $\frac{V}{t} = \frac{\pi r^4 \Delta P}{8 \mu L}$, $V$, $t$, $R$, $\Delta P$, $L$, and $\mu$ are introduced as volume, time, and radius of capillary, pressure drop, and length of capillary and dynamic viscosity of fluids respectively. The modified formula for the capillary systems suggested as Poiseuille equation or Hagen–Poiseuille equation as follows:
\[
\mu = \frac{\pi r^4 \rho g h t}{8 V (L + nr)} - \frac{m \rho V}{8 \pi (L + nr) t}
\]  
(2.3)

Where “\(r\)” is the radius and \(L\) is the length of the capillary, \(h\) is the effective height of standard liquid column, \(\rho\) is the liquid density, \(V\) is the discharged volume at time \(t\), and \(m\) and \(n\) are constants which can be determined experimentally. \(\rho g h\) is the pressure which can be replaced by \(\Delta P\) (the pressure drop along the capillary), and \(nr\) is defined as the end correction (for liquid exit and entry ) which basically corrects for surface tension effects [104-106].

The capillary viscometer which comprises the parts below:

1. Cap nuts
2. Washers
3. Holding plate
4. Silicone rings
5. Fixing plate
6. Silicone O-ring
7. Quick-release closure
8. Tube ends
9. Tempering Jacket

![Figure 2.4: Falling ball viscometers schematic](image.png)

Li et al. [77] measured the viscosity of water-based CuO by a capillary viscometer. In this study, they mentioned that the capillary tube diameter probably influences the apparent viscosity for higher volume concentrations and lower temperature- where the viscosity is higher.

He et al.[89] also measured TiO\(_2\) in distilled water using Ubbeholder capillary viscometer (Fisher Scientific). Chevalier et al. [90] studied SiO\(_2\)/water and SiO\(_2\)/EG viscosity for particle sizes of 35, 94, and 190/\(\mu\)m, particle volume concentration from 1.4% to 7% by micro machined capillary viscometers.

Wang and Li [107] measured viscosity of water-based CuO and Al\(_2\)O\(_3\) under different PH range using capillary viscometer.

Wang et al. [108] investigated aqueous CuO nanofluid as a working fluid in steady cooling condition and measured the viscosity by a capillary viscometer.
Orifice viscometers (efflux type) like draining vessel are very common in oil and industry viscosity measurements. These kinds of viscometers usually consist of reservoir (flow cup), an orifice and a receiver.

The design concept of these viscometers is based on the Hagen-Poiseuille Law (constant volume efflux of liquid in a capillary is proportional to the viscosity of the fluid).

Concerning Draining vessel method, time will be counted for a constant volume of liquid which flows through a small orifice in bottom of the cup. Then, viscosity is derived from look-up tables [104]

2.2.2.2. **Drag Type Viscometers:**

Drag type viscometers are also categorized as falling object, rotational and bubble tube methods.

2.2.2.2.1. **Falling Object (ball) Viscometers**

Is a type of viscometer in which the principle is to specify the time of falling ball with known diameter and density through a liquid which is put inside a vertical glass tube of known diameter and length.

The liquid has a dynamic viscosity, which results in a resistance against the ball downward movement. This frictional force is derived from the Stokes's law. The falling ball method is based on Stokes' law which is expressed as below:

\[
\mu = \frac{2 \pi r^2 (\rho_s - \rho_{liq})}{g} \frac{1}{v}
\]  

(2.4)

Where \( g \) is the gravitational constant, \( r \) is the radius of the ball, \( \rho_s \) and \( \rho_{liq} \) are the density of the sphere and the liquid, respectively and \( v \) is the ascent velocity of the sphere [104].

The falling ball viscometer, which is used in the experiments, comprises the parts below:

1. Stand
2. Viscometer
3. Spirit level
4. Adjusting screw
5. Adjustment screw
6. Falling tube
7. Upper plate
8. Lower plate
9. Water bath jacket
10. Olive shaped tubes
11. Fastening screw for thermometer
12. Screw neck
13. Sealing washer
14. Bearing
15. Nuts
16. Upper locking plug
17. Lower locking plug
18. Cap
19. Sealing

![Figure 2.5: Falling ball viscometers schematic](image-url)
There have been some considerations such as the expansion of the ball and also designing the ball with a diameter of less than 1/10 compared to the crucible diameter to make the falling ball viscometer more accurate[109, 110].

Recently, Feng et al. [111] have measured 5% volume fraction SiO$_2$ nanofluid using a falling ball viscometer.

### 2.2.2.2. Rotational Viscometers

This is a kind of viscometer in which the principal of operation is to drive a spindle (which is immersed in the test fluid) through a calibrated spring. Torque on the cylinder rotating in the sample is applied to calculate the viscosity. The viscous resistant of the sample against the cylinder is measured by a spring deflection and spring deflection is measured with a rotary transducer. This genre of viscometers are consisting of two concentric cylinders namely a bob (spindle) and a crucible (cylinder).

The measurement range of a rotary cylinder viscometers (in centipoises / milliPascal seconds) is determined by the spindle rotational speed, size and shape of the rotary spindle, container in which spindle is rotating in, and the full-scale torque of the calibrated spring and so forth.

In a constant rotational speed the viscosity of fluid can be obtained using the formula as below:

$$\mu = \left(\frac{1}{r_1^2} - \frac{1}{r_0^2}\right) \frac{M}{8\pi^2 nh}$$  \hspace{1cm} (2.5)

Where $M$ is the torque, $n$ is the number of revolutions per second, $r_1$ is the radius of spindle, $r_0$ is the radius of spindle crucible, and $h$ is the height of spindle [104].

Duangthongsuk and Wongwises [112] experimentally studied viscosity of water-based TiO$_2$ including nanoparticles with average diameters of 21 nm and a particle volume concentration of 0.2–1 vol.
percentage by a Bohlin rotational rheometer. Yang et al. [113] were also used Bohlin CVO rheometer (rotary rheometer) for their experiments. Namburu et al. [85] worked experimentally on water/EG (60:40 wt %) based CuO. They measured viscosity of nanofluids with particle volume fraction of 0% to 6.12% by a coaxial cylinders rheometer (HaakeRheostress RS600).

2.2.2.3. **Bubble (Tube) Viscometers**

It is a kind of viscometer in which bubble movement in liquid, in a certain period of time, is measurement principle. This kind of viscometers is used to determine kinematic viscosity quickly. Time at which the bubble rises inside the sample is proportional to the viscosity of liquid. The slower the bubble rises, the more viscose fluid is would be, and vice versa. In this kind of viscometer, it is needed to know almost a close estimation of fluid viscosity to choose the proper tube for measurement [119].

![Figure 2.7: Three bubble viscometers in different viscosity ranges](image)

2.2.2.3. **Vibrational/Oscillating Viscometers:**

The most common methods of oscillating (vibrational) measurements are oscillating vessel, palate and drop viscometers.

2.2.2.3.1. **Oscillating vessel viscometer**

Is a kind of viscometer in which the principle is oscillation damping by liquid in a time period. Sample of liquid put in a vessel and exposed to a motion in vertical axis. The viscosity of sample is determined by considering the decrement of motion in a certain period of time [104].

2.2.2.3.2. **Oscillating plate method**

This method is based on vibration of a flat plate and amplitude of plate oscillating inside the test sample. The oscillation of the flat plate with a constant driving force is measured in both liquid and air.

For the measurement, the following equation with some assumption can be used [104, 114 and 115]:

$$\rho \mu = \frac{R^2}{\pi A^2 f} \left( \frac{f_{a} E_{a}}{f_{E}} - 1 \right)^2 = K_0$$  \hspace{1cm} (2.6)
where the \( \rho \) is density, \( R_m \) is the real digit of the mechanical impedance, \( f \) and \( f_a \) are frequencies of plate oscillation in liquid and air, \( E \) and \( E_a \) are also the amplitude of oscillation of plate inside the air and sample and \( A \) is the palate effective area.

Concerning the formulation on which the measurement is based the assumption should be considered as below:

1. Sample test should be Newtonian one,
2. The constant force exerts and the amplitude of it should be in a way no turbulent flow happen.
3. There should be no slipping between the plate and the fluid.
4. Oscillating palate size should be large enough- larger than one oscillation wavelength.
5. The end damping influence of plate is negligible.
6. Vessel size should also be large enough so that the effects of reflected wave from the wall are negligible.

**2.2.2.3.3. Oscillating (levitated) drop method**

It is a kind of method by which both surface tension and viscosity of liquids are measurable. In this method, there is no need to external forces and it can be done by falling a droplet [118].

The measurement is based on the principle that relates the frequencies of liquid surface oscillation with surface tension using Rayleigh’s formula [116]. Cummings and Blackburn formula [117] is a corrected version of Rayleigh’s formula by which the earthbound levitation. Moreover, the viscosity of fluids are measured based on similar principle. The damping constant by which the viscosity measures is as following:

\[
\Gamma = \frac{20\pi}{3} \left( \frac{ru}{m} \right) \tag{2.7}
\]

Where \( m \) and \( r \) are mass and radius of droplet, respectively and \( \mu \) is viscosity. Meanwhile, to achieve a correct measurement the conditions below should be met:

1. Droplet of liquid should be spherical.
2. The oscillation have to stand in a time for about \( t = \frac{1}{\Gamma} \)
3. There should be no extra damping mechanisms [104].
2.3. Stability

To provide better cooling using nanofluids in industry, they are expected to possess long-term stability which should be noted during preparation and synthesis of nanofluids. Indeed, to utilization of nanofluids in practice, stability might be one key issue. Therefore, reasons for fast sedimentation of nanoparticles or nanotubes should be recognized and dispelled.

2.3.1. Effective parameters on stability

To consider and evaluate stability of nanoparticles inside the base fluid, Stokes law, suggesting an equation for sedimentation velocity calculation of small spherical particles, states that:

\[ v = \frac{2r^2}{9\mu} (\rho_p - \rho_L) \]  

(2.8)

Where \( r \) is radius of particles; \( \mu \) is viscosity of liquid; \( \rho \) is density while \( p \) and \( L \) subscripts are showing particles and liquid, respectively. Finally, \( g \) is gravity force which is the main reason of sedimentation. Three forces acting on suspended particle are including buoyancy force, drag force and body force. Buoyancy and drag forces are acting upward and resisting against body force acting downwards resulting from gravitational attraction [133].

As it was mentioned earlier, higher suspension time is desired in nanofluids. Therefore, some remedies can be offered extracting from Stokes law to improve stability of nanofluids. To decrease sedimentation velocity as much as possible, radius of particle should be kept as small as possible. Since sedimentation velocity is proportional to square of radius, reducing size of nanoparticles will lessen it dramatically. Wu et al. declared that preparation of stable nanofluid would strongly depend up on particle size [134]. Moreover, base fluid and particle should be chosen in such a way that density difference of them would be kept as less as possible. Increasing viscosity of base fluid would be another way to increase stability of particle.

In general, there are three different techniques utilized by researchers to improve dispersion behavior of nanofluids and to minimize particles aggregation which acts against long-term stability. However, clustering and aggregation have been reported as features increasing thermal conductivity of nanofluids [36, 51]. Therefore, in preparation both issues should be taken into account to make a balance between stability and thermal conductivity, having a stable thermal conductive nanofluid.

Those three common techniques for making stable nanofluid are stated below:

- Addition of surfactant
- pH control
- Ultrasonic agitation (vibration)

Addition of surfactant and pH control are two techniques to prevent clustering and agglomeration while ultrasonic vibration is applied to break down agglomeration. Some researchers have used all three techniques to improve stability of nanofluid such as Zhu et al. [62], Wang et al. [135] and Pantzali et al. [136] while others just applied one [137] or two methods [138].
2.3.1.1. Addition of surfactant

Surfactants can be defined as chemical compounds added to nanoparticles in order to lower surface tension of liquids and increase immersion of particles. Several literatures talk about adding surfactant to nanoparticles to avoid fast sedimentation; however, enough surfactant should be added to particle at any particular case.

In researches, several types of surfactant had been utilized for different kinds of nanofluids. The most significant ones could be listed as below:

- Sodium dodecylsulfate (SDS) [139-141],
- SDBS [62, 142],
- Salt and oleic acid [141,143],
- Cetyltrimethylammoniumbromide (CTAB) [55,142],
- Dodecyl trimethylammonium bromide (DTAB) and sodium octanoate (SOCT) [144],
- Hexadecyltrimethylammoniumbromide (HCTAB), [145]
- Polyvinylpyrrolidone (PVP) [146]
- Gum Arabic [147]

It should be pointed out that this technique cannot be applicable for nanofluids working in high temperature on account of probable damage of bonding between surfactant and nanoparticle [134, 148]. Some researchers reported above 60°C as critical temperature by doing some experiments [55, 149].

2.3.1.2. pH Control

Stability of nanofluid is directly related to its electro-kinetic properties; therefore, pH control of them can increase stability due to strong repulsive forces [62, 150]. As an example, simple acid treatment done by Xie et al. could cause nice stability of CNT in water [151].

General speaking, two types of behavior including attraction and rejection occurs among particles due to van der Waals and electrostatic forces and it is possible to control these forces by means of pH control. Li et al. have accomplished research to study effect of pH and SDBS surfactant on thermal conductivity of Cu-H2O nanofluid [152].

Lee et al. investigated various pH values for Al2O3 nanofluid and observed decrease or increment of agglomeration by changing pH [153]. Moreover, Lee studied change of size particle and pH value for Al2O3/DI nanofluid containing some other additives to keep pH constant in a particular test case [149].

Finally, it should be noted that optimized pH value is different from one sample to another. For instance, suitable pH value for alumina, copper and graphite dispersed in water are around 8, 9.5 and 2, respectively [107].

2.3.1.3. Ultrasonic agitation (vibration)

After preparation of nanofluids, agglomeration might occur over the time which results in fast sedimentation of nanoparticles due to enhancement of downward body force. Manson et al. investigated two different nanofluids; carbon black/water and silver/silicon oil and they utilized high energy of cavitations for breaking clusters among particles [154].
As it was mentioned before, all three methods might be used for one specific sample during synthesis and preparation; yet, it is difficult to make stable nanofluid and rare to maintain nanofluids synthesized by the traditional methods in a homogeneous stable state for more than 24 h [155].

### 2.3.2. Stability Evaluation Method

Among limited number of studies on stability of nanofluids, evaluation of them has been considered by some researchers and six different methods were utilized which can be listed as below:

- UV–Vis spectrophotometer
- Zeta potential test
- Sedimentation photograph capturing
- TEM (Transmission Electron Microscopy) and SEM (Scanning Electron Microscopy),
- Sedimentation balance method
- $\omega$ method

#### 2.3.2.1. UV–Vis spectrophotometer

Ultra Violet–Visible spectrophotometer is one of the most common methods used to investigate stability of nanofluids due to its ease of use and fast analysis. It has been utilized to magnitude stability of suspensions in nanofluids; however, viscosity of base fluid would be known as one constraints of this method [156]. This method is based on different wavelengths of light in which it can be scattered or absorbed by other materials. It is known when light is passing through fluids, intensity of it changes by absorption and scattering.

Jiang et al. were first who suggested using UV-Vis spectrophotometer for evaluating stability of nanofluids [140]. Chang et al. also applied this method for inspection of stability of CuO/DW and Cu/DW nanofluids [157].

#### 2.3.2.2. Zeta potential test

Stabilization theory [74] states that increasing zeta potential, scientific term for electrokinetic potential in colloidal system, results in high stability of the suspension. It is also well known that electrostatic repulsion between the particles would be increased in high absolute value of zeta potential [147].

Stability of Cu nanoparticles of 0.05% weight concentration inside water has been inspected by Wang et al. using zeta potential test [135].

Vandsburger tabulated different values of zeta potential in mV and stated stability situation of the suspension in any specific zeta potential value which can be observed in Table 2.1.

<table>
<thead>
<tr>
<th>Zeta potential (Absolute value (mV))</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Little or no stability</td>
</tr>
<tr>
<td>15</td>
<td>Some stability but settling lightly</td>
</tr>
<tr>
<td>30</td>
<td>Moderate stability</td>
</tr>
<tr>
<td>45</td>
<td>Good stability, possible settling</td>
</tr>
<tr>
<td>60</td>
<td>Very good stability, little settling likely</td>
</tr>
</tbody>
</table>
2.3.2.3. Sedimentation photograph capturing

It can be introduced as a basic method to evaluate stability of nano suspensions inside the fluid. After preparation of nanofluid, it would be kept in a stationary standing condition inside glass tubes and settlement of particles would be recorded continuously by capturing photos. Waiting time for capturing photos links up with quality of nanofluid during preparation and well use of applied methods to make a stable nanofluid. For instance, Wei et al. tested their samples within 24 hours after preparation [30]. Wang et al. investigated sedimentation of Al₂O₃ inside water after 7 days capturing using this method as well [153].

2.3.2.4. TEM (Transmission Electron Microscopy) and SEM (Scanning Electron Microscopy)

These two are known as suitable tools for study and determination of microstructures. Shape, size and distribution of nanoparticles can be distinguished using them. Moreover, their aggregation which is related to stability of nanofluid could be monitored also [134]. They are capable to capture photos in small sizes to reveal suspension situation of nanoparticles inside the fluid after preparation. Figure 2.8 shows TEM and SEM pictures from cu nanofluid and CNT [1]

![Figure 2.8: TEM left, SEM right][1]

2.3.2.5. Sedimentation balance method

In this method, accurate balance with tray, which is able to collect nanoparticles while sedimentation, would be immersed inside nanofluid immediately after preparation phase. Monitoring weight of nanoparticles, suspension fraction of them is calculated by following formula:

\[
F_s = \frac{(W_T - W)}{W_T}
\]  

(2.9)

Where \(F_s\) is suspension ethylene glycol fraction at an accepted time; \(W_T\) is total weight of nanoparticles inside the base fluid and \(W\) is weight of settled nanoparticles at an accepted time [147].

2.3.2.6. \(3\omega\) method

In this method, stability of suspensions can be evaluated considering thermal conductivity growth caused by the nanoparticle sedimentation in a wide nanoparticle volume fraction range [156]. A few literatures were found using \(3\omega\) method for investigation stability of nanofluids [67].
3. Thermal Conductivity Measurement

In this section, experimental results and data analysis regarding thermal conductivity of several nanofluids will be investigated. However, instrument calibration, bath performance and finding suitable combination of power and time for TPS analyzer has been accomplished in advance and related results can be observed.

3.1. Experimental result for thermal conductivity

This section is including thermal conductivity measurement of nanofluids. Firstly, applied method, transient plane source (TPS) method, has been introduced. Afterwards, calibration of the analyzer and sensor as well as bath performance has been accomplished. Finding a proper combination of power and time was other challenge of the measurement. Finally, measurement results of nanofluids have been found.

3.1.1. Transient plane source method

As it was mentioned earlier, thermal constant analyzer technique or transient plane source (TPS) is a method to measure thermal conductivity of materials. Schematic diagram of the whole setup used to measure thermal conductivity of nanofluids at energy department of KTH has been depicted in Figure 3.1.

![Figure 3.1: Experimental setup of Transient Plane Source (TPS) method](image)

Hot Disk AB [158] is one of the companies that has already commercialized this method. This company fabricates a special sample holder merely from stainless steel to keep liquids. The schematic diagram for the sample holder and the sensor are shown in the Figure 3.2. The sensor is sandwiched between two metallic blocks of the sample holder. The sample holder is placed in a metallic shell located directly inside a cooling bath. In this study, TPS method is utilized to measure thermal conductivity of nanofluids
As it can be seen in Figure 3.1, sample holder should be located inside a thermal bath with constant temperature. Hot Disk AB [158] produces thermal constant analyzer in different types for various purposes and TPS 2500S analyzer has been utilized for thermal conductivity measurement in this study.

3.1.2. Calibration of the instrument

One of the primary processes used to maintain accuracy of an instrument is calibration. Indeed, calibration is a routine of adjusting an instrument to provide result for a sample in a reasonable range. TPS analyzer has been calibrated by measuring three different fluids with known values of thermal conductivity including Distilled water (DW), ethylene glycol (EG) and mixture of water and ethylene glycol (50% by volume). Several references were investigated to find proper values for thermal conductivity of distilled water in different temperatures among which NIST data [159] has been appointed as the criteria. This test has been done in three different temperatures including 20, 40 and 60 °C. As it can be observed in Figure 3.3, closest value to the NIST measured data for thermal conductivity of DW can be achieved when temperature is 20 °C. Increasing temperature results in diversion from NIST data.
Ramires et al. [160] tested thermal conductivity of water and results of their measurements confirm NIST database, interestingly.

Figure 3.3 discloses that thermal conductivity measured by applying TPS method using Hot Disk AB sensor and analyzer is trustable since variation from NIST data is less than 5 percent. Authors also investigated two different types of sensor to test if they can show better result than initial one. However, measured data from sensor 1 showed best values for thermal conductivity.

![Figure 3.4: Thermal conductivity of ethylene glycol (EG) at different temperatures](image)

Ethylene glycol (EG) is the other sample experimented during calibration process. Firstly, several sources reporting thermal conductivity of EG has been considered and reviewed. Data values for thermal conductivity of ethylene glycol from ASHRAE handbook [161] have been considered as the criteria with which validity of other data would be evaluated. Moreover, measurement data performed by two other parties, Beck et al. [162] and Assael et al. [163] absolutely follow ASHRAE data of thermal conductivity.

This scenario can be observed in Figure 3.4 in which acceptable range of ASHRAE data between plus/minus 5 percent of error range is shown by dash lines. Two measurements were conducted to calibrate TPS analyzer and results are illustrated in Figure 3.4 namely, first and second measurement. It can be seen that increasing temperature leads to digression of measurement values of thermal conductivity from ASHRAE data. The reason might be convection of fluid in higher temperatures. Later on, it will be described that lowering applied power and time to the sensor can solve this problem. As it is obvious in the figure, thermal conductivity is out of the acceptable range within first measurement at temperature 50°C. Nonetheless, both first and second measurements show very similar values that is confirmation of the fact that measurement data in this method would be repeatable. In measurement process, data repeatability of any instrument is its essential benefit.

Finally, thermal conductivity of mixture fluid containing ethylene glycol and distilled water, with portion of fifty volume percentage for each of them, has been measured. It can be viewed in Figure 3.5 that measured data is within acceptable range of result from ASHRAE handbook [161]. It should be pointed out that same behavior as EG and DW occurs for the mixture. Meanwhile, closest data to reference one is in temperature of 30°C in this case.
It can be concluded that since results measured by TPS method for three different fluids with known values of thermal conductivity were in reasonable ranges, experimental setup including TPS analyzer and sensor is calibrated properly. Moreover, reliability of measurement instruments is a key issue which has been proved by measuring thermal conductivity of water several times at 20 °C. Results regarding setup reliability are summarized in Table 3.1.

### Table 3.1: Thermal conductivity of distilled water

<table>
<thead>
<tr>
<th>Temperature</th>
<th>1st Test</th>
<th>2nd Test</th>
<th>3rd Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.586238966</td>
<td>0.590490765</td>
<td>0.588347526</td>
</tr>
<tr>
<td>20</td>
<td>0.594013637</td>
<td>0.583086708</td>
<td>0.58548373</td>
</tr>
<tr>
<td>20</td>
<td>0.588279722</td>
<td>0.580907198</td>
<td>0.588316229</td>
</tr>
<tr>
<td>Average</td>
<td>0.589510775</td>
<td>0.584828224</td>
<td>0.587382495</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.00403088</td>
<td>0.005023529</td>
<td>0.00164453</td>
</tr>
</tbody>
</table>

Figure 3.5: Thermal conductivity of mixture of ethylene glycol and distilled water (50 vol%) at different temperatures.
3.1.3. Thermal Bath Performance

As it was illustrated in Figure 3.1, measurement setup includes a thermal bath in which sample holder would be kept. In order to skip the effect of vibration, it has been recommended to keep sample holder inside a shell connected to a frame. The bath is utilized to keep the sample temperature constant. Furthermore, it should be noted that thickness of sample holder brings about thermal mass which provides more appropriate condition for keeping the temperature constant inside the bath. However, authors aimed to check performance of the bath and see if the temperature of sample during measurement would follow set point temperature of the bath.

Sample holder, filled with water, was not put inside the bath directly, but it was put inside a shell which is in contact with water inside the bath. Seven thermocouples calibrated earlier have been installed inside the sample holder, bath and shell to measure their temperatures. Generally, sample holder (clamp) is including three injection pipes in which sample is inserted or exited and three thermocouples were installed inside them numbered from 1 to 3. Two thermocouples are installed inside the shell, number 4 and 5 in the figure. Thermocouples number 6 and 7 are installed inside the bath in contact with water which can be observed in the Figure 3.7 as well. It should be stated that avoiding direct contact of thermocouples number 6 and 7 with surface of thermal bath was taken into account since these two thermocouples were meant to measure the temperature of water.

In this study, two different situations of the shell, namely wet and dry shell were tested. It was predictable that dry shell, shell without water inside, cannot transfer the heat well especially in high temperatures even though it was a recommendation from the company.

3.1.3.1. Dry shell

In the first instance, measured thermal conductivity values of DW at different temperatures for dry shell have been plotted. Figure 3.8 illustrates temperature variation inside the clamp, shell and bath at 20 °C. Moreover, Average value for each of them and comparison with set point temperature has been depicted in Figure 3.9. It is obvious in the figure that temperature inside the clamp is in desired range, approximately and diversion from adjusted temperature can be considered in a reasonable error range.
Afterwards, bath temperature was changed from 20 °C to 30 °C and monitoring temperature variation of different thermocouples has been plotted in Figure 3.10. It can be observed that temperature of the fluid inside the sample holder (clamp temperature) cannot converge set point temperature after 50 minutes.
Even after a long time, temperature of the sample is around 27 °C while set point temperature is 30 °C. The conclusion can be taken that having dry shell may not fulfill prerequisite of the measurement which is retaining the sample in a constant temperature. Besides, it takes long period of time for fluid inside the sample holder to be adjusted in a constant temperature. This story can be observed in Figure 3.11 and Figure 3.12. The former shows measured temperature by all seven thermocouples separately while the latter illustrates average value of temperature for clamp, shell and bath together with adjust temperature of the bath.
It is even worse for higher temperatures such as 40 °C and 50 °C where temperature difference between fluid and adjust temperature is higher. When temperature is set to 40 °C, temperature difference is about 6.5 °C between set point and fluid whilst this value is about 8 °C when the set point temperature is 50 °C. Graphs regarding these two set point temperatures as well as average values and changing temperature from 30 °C to 40 °C and from 40 °C to 50 °C has been depicted in appendix A.

Finally, difference between adjusted and clamp temperature in dry shell experiment has been illustrated in Table 3.2 and Figure3.13.

| Table 3.2: Temperature difference from set point for dry shell |
|-------------------------------|----------------|
| Set point (°C)                | Temperature Difference (°C) |
| 20,00                         | 0,14               |
| 30,00                         | 3,10               |
| 40,00                         | 6,42               |
| 50,00                         | 8,16               |
3.1.3.2. Wet Shell

In the second instance, water was supplemented into shell to improve heat transfer performance between bath and sample inside sample holder. In other words, in this case air gap between shell and sample holder was filled with water.

Figure 3.14 displays temperature variation of different sections versus time. Compared to clamp and shell, graphs related to temperature of bath 1 and bath 2 have more fluctuation. It might be due to effect of ambient temperature or adjacency of thermocouples to the pump.
Figure 3.15 can show average value of each section for wet shell and graph does not reveal much difference between set point which is 20 °C and measured sample temperature.

The conclusion can also be achieved from Figure 3.15 that bath and sample have very similar temperature values; however, problem exists between set point and sample temperature since about 1 °C difference exist. It will be proven that this difference will not affect thermal conductivity measurement in future.

Figure 3.16 plots temperature variation from 20 °C to 30 °C for wet shell versus time. It can be seen that after 10 minutes temperature would be stable and all three parts i.e. clamp, bath and shell will roughly show same temperature.
Temperature versus time graph relating 7 installed thermocouples for wet shell in 30 °C has been depicted in Figure 3.17. It is noteworthy to be mentioned that this test has been accomplished immediately after full transient of temperature from 20 °C to 30 °C shown in Figure 3.16 above.

In appendix other measured temperatures for wet shell has been depicted which are including data at 40 °C and 50 °C set point temperatures as well as average values and transient temperature from 30 °C to 40 °C and from 40 °C to 50 °C. It can be stated that transient time for both cases is about 10 minutes which means waiting time would be 10 minutes for launching measurement of thermal conductivity after changing set point temperature.

Comparative results at all temperatures of wet shell can be seen in following figure and table. Table 3.3 states that maximum temperature difference (1.50 °C) occurs when set point temperature is 50 °C. This fact has been illustrated in Figure 3.18 as well.

![Figure 3.17: Temperature monitoring of bath and sample holder over the time at T=30°C for wet shell](image)

<table>
<thead>
<tr>
<th>Set point (°C)</th>
<th>Temperature Difference of Wet shell (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.86</td>
</tr>
<tr>
<td>30</td>
<td>1.05</td>
</tr>
<tr>
<td>40</td>
<td>1.19</td>
</tr>
<tr>
<td>50</td>
<td>1.50</td>
</tr>
</tbody>
</table>
3.1.3.3. Comparison between dry and wet shell

Finally, comparative study has been done for dry and wet shells and it has been proved that wet shell can absolutely result in better heat transfer performance rather than dry shell. Figure 3.19 shows temperature difference versus adjusted temperature graph of wet and dry shells. Based on results, wet shell would be more suitable option for keeping the temperature of the sample constant.

Overall, thermal stability of the sample holder occurs after very long time because of the air gap between the sample holder and the shell for dry shell. In the second experiment, the sample holder filled with water and kept in the shell in the bath equilibrium condition of $T=20^\circ$C. The temperature of the bath
increased from $T=20^\circ C$ to $T=29.1^\circ C$ and the temperatures of the bath and inside the sample holder were recorded. Figure 3.20 shows that it takes around 10 min for the bath to reach the temperature, $T=29.1^\circ C$; however, even after 50 min (Dry, the red line) the temperature inside the sample holder does not reach the bath’s temperature. In the second experiment some water was added inside the shell to fill the air gap and to have better thermal contact between the sample holder, the shell, and the water bath. The results in Figure 3.20 shows that the temperatures inside the sample holder and the bath are the same after around 15 minutes (Wet, the blue line). These two experiments prove that temperature stability can be reached much faster by introducing a heat transfer media (water in this case) for a better thermal contact in the sample holder setup.

*Figure 3.20: Temperature monitoring of sample holder over the time from $T=20^\circ C$ to $T=30^\circ C$ for wet and dry shells*
3.1.4. Power and Time Combination

Hot Disk sensor utilized inside the clamp consists of an electrically conducting pattern made from Nickel with Kapton insulation. Nickel is chosen due to its high resistivity while Kapton insulation is very flexible on account of its mechanical properties and long life-time. It can be observed in Figure 3.21 that pattern is in the shape of double spiral [164].

![Figure 3.21: Hot Disk sensor with Kapton insulation](image)

The basic principle behind the thermal conductivity measurement using thermal analyzer and sensor is to supply a constant power during limited time to sensor. Afterwards, temperature of the sensor will increase while it acts as thermometer and resistance, simultaneously. Temperature increment of the sensor influences on its resistance and by recording and analyzing it, thermal conductivity and thermal diffusivity can be determined from one single transient recording [164].

As it was mentioned, specific power and time should be selected which vary from one material to another especially when they are in different phases. In calibration phase, deviation of measured thermal conductivity from expected values was increasing by temperature increment. It has been assumed that the reason might be improper value for power or time in that case. Therefore, different combinations of power and time by changing temperature have been tested to evaluate measured thermal conductivity values and select the best combination for each single temperature afterwards. It should be noted that recommended power and time were 0.02 W and 5 s, respectively.
Figure 3.22: Power/Time combinations for measuring thermal conductivity of DW at T=20 °C

Figure 3.22 illustrates graph of thermal conductivity measurement of water versus number of experiments with different combinations of power and time. It can be observed that measured data has been compared with NIST as the reference data at 20°C. Although, some combinations vary within the range of plus/minus 5 percent from NIST data, the most accurate value for thermal conductivity is obtained when power is 0.02 W and time of power supplement is 5 seconds. Some combinations are totally out of the range which is due to high power and long time (high energy) leading to convection in the sample. It is worth to mention that for each combination, tests have been repeated three times shown with diamond-shaped markers in graph above.

Several tests had been run to control if selected power and time from last experiment could render repetitive results. In fact, repeatability of the test was key concern of the authors. The test had been repeated for 20 times and Figure 3.23 shows the result of the measurement as well as comparison with NIST data. Measured data of this test will confirm that selected power and time combination is appropriate when temperature is 20 °C.
Figure 3.23: Confirmation of selected combination at T=20°C and comparing with NIST data

Figure 3.24: Power/Time combinations for measuring thermal conductivity of DW at T=30°C
Finding suitable combination of power and time for water at 30°C was further step. Similar procedure followed and results are depicted in Figure 3.24. Testing several combinations of power and time and comparing with thermal conductivity value from NIST database, power of 0.02 watt during 4 seconds have formed suitable combination when temperature is 30°C. In Figure 3.25, thermal conductivity versus number of experiments of any single combination has been shown. It should be noted that supplying too much power in a long time can result in convection that can be viewed in the figure. For instance, it occurs when power is 0.02 W or 0.03W or 0.04 W and time is 9 seconds.

To verify that selected power and time are appropriate choice when temperature of the sample has been kept at 30°C, its thermal conductivity has been measured 20 times in row with 5 minutes time interval and Figure 3.25 is showing results of the test.

![Confirmation of Selected Combination in T=30°C](image)

As it can be seen in Figure 3.25, all measured data vary within the range of (+/-) 3% from NIST data which can be considered as a valid result and selected combination of power and time, P=0.02 W and t=4s, is suitable.

Same procedure, as mentioned for water at 20 °C and 30 °C, followed at 40 °C to discover appropriate combination of power and time. In Figure 3.26, thermal conductivity measurement data for different combinations of power and time can be observed. 0.01W and 5 seconds, for power and time respectively, has been introduced the best when sample temperature is 40 °C. In addition, on account of higher temperature of sample, convection occurs earlier compared to lower temperatures such as 30 °C and 20 °C. For instance, when power is 0.04 W during 5 seconds or 7 seconds, convection interrupts acceptable results from the measurement.

To explore if selected combination of power and time is suitable and test result is repeatable, confirmation test was run. In Figure 3.27, it can easily be observed that measured values for thermal conductivity would follow NIST data, interestingly.
**Figure 3.26:** Power/Time combinations for measuring thermal conductivity of DW at T=40°C

**Figure 3.27:** Confirmation of selected combination at T=40°C and comparing with NIST data
Finally, bath temperature was set at 50°C and when temperature of the sample was stabilized; thermal conductivity measurement has been accomplished while different combinations of power and time were under consideration.

Thermal conductivity values for different combinations in addition to their comparison with NIST data has been displayed in Figure 3.28. It has been concluded that when power is 0.01W and time period for supplying this power is 4 seconds, best value could be obtained. In this case, convection occurs faster compared to other temperatures, manifestly. Some data are totally out of the range due to high convection that leads to undesirable values for thermal conductivity.

Similarly, selected power and time combination is supposed to be confirmed by means of test repetition for 20 times. Outcomes of confirmation test state that introduced combination of power and time is a fitting option. Figure 3.29 shows thermal conductivity versus number of experiments. In this graph, result are compared to NIST data. It can be observed that measured data are in range of +/- 5% of NIST data.
In brief, appropriate values of power and time combination at any single temperature has been stated in Table 3.4.

**Table 3.4: Selected power and time combination for different temperatures**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Power (w)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.02</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>0.01</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>0.01</td>
<td>4</td>
</tr>
</tbody>
</table>
3.1.5. Thermal Conductivity Measurement of Nanofluids

It has been mentioned that several features can influence on thermal conductivity of nanofluids among which effect of following have been investigated in this study:

- Particle Concentration
- Sonication Time
- Particle Size
- Particle Shape
- Alcohol
- Temperature

It should be mentioned that ethylene glycol utilized to prepare nanofluids has 99.99% pure EG and antifrogen (AFN), based on monoethylene glycol including anticorrosion additives, is a universal heat transfer fluid, antifreeze and corrosion inhibitor for refrigeration, heat pump and hot water heating systems from Clariant company.

3.1.5.1. Particle Concentration

Concentration of particles would be regarded as one of the most significant features affecting thermal conductivity of nanofluids. Basically, it is expected that adding nano particles would improve heat transfer performance of nanofluids and also would increase thermal conductivity of them. It is also predictable that the more concentration, up to a certain reasonable limit, would cause the more increase in thermal conductivity.

Four different nanofluids composing of ethylene glycol (EG) as basefluid and cerium oxide (CeO$_2$) as nanoparticle, with 0.5 and 1 weight percentage concentration, have been investigated. Figure 3.30 displays thermal conductivity versus temperature graph for samples mentioned above. It states that when weight concentration of CeO$_2$ nanoparticles is 0.5%, thermal conductivity of nanofluid is more than basefluid. Moreover, when weight concentration of nanoparticles increases from 0.5% to 1%, thermal conductivity of nanofluid raises.

![Figure 3.30: Thermal conductivity of EG/CeO$_2$ nanofluids at different temperatures](image)

---

48
In Table 3.5 thermal conductivity enhancement of this set of nanofluids can be observed. Among them nanofluid with 1 weight percentage of cerium oxide shows greatest increment of thermal conductivity. There are three types of nanofluid with same concentration of nanoparticles showing different values of enhancement. It might be due to the variety in preparation phase of them which will be discussed in section 3.1.5.7.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>CeO₂ (0.5 wt%) KTH_MS029</th>
<th>CeO₂ (0.5 wt%) KTH_MS026</th>
<th>CeO₂ (0.5 wt%) KTH_MS015</th>
<th>CeO₂ (1 wt%) KTH_MS014</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.76</td>
<td>1.52</td>
<td>3.94</td>
<td>8.36</td>
</tr>
<tr>
<td>30</td>
<td>0.68</td>
<td>1.15</td>
<td>3.40</td>
<td>8.14</td>
</tr>
<tr>
<td>40</td>
<td>0.81</td>
<td>1.26</td>
<td>3.85</td>
<td>9.00</td>
</tr>
<tr>
<td>50</td>
<td>0.54</td>
<td>1.08</td>
<td>3.39</td>
<td>8.92</td>
</tr>
</tbody>
</table>

Next experiment result is relating thermal conductivity of antifrogen-based (Anti Freeze Concentrate) nanofluids with various concentrations of cerium oxide nanoparticles. In Figure 3.31, it has been shown that thermal conductivity of AFN/CeO₂ nanofluid is increasing by raising concentration of particles from 1 weight to 3 weight percentages, continually. It also can be seen that thermal conductivity is increasing by raising temperature of the sample.

![Figure 3.31: Thermal conductivity of AFN/CeO₂ nanofluids at different temperatures](image)

As it was mentioned, adding more nanoparticles can result in increment of thermal conductivity. Table 3.6 shows percentage of increment for each specific concentration by changing temperature from 20 °C to 50 °C.
### Table 3.6: Thermal conductivity enhancement of AFN/CeO$_2$ nanofluids at different temperatures

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>AFN-CeO$_2$ 1%</th>
<th>AFN-CeO$_2$ 2%</th>
<th>AFN-CeO$_2$ 3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.8</td>
<td>4.5</td>
<td>6.8</td>
</tr>
<tr>
<td>30</td>
<td>2.6</td>
<td>4.0</td>
<td>7.2</td>
</tr>
<tr>
<td>40</td>
<td>2.2</td>
<td>5.4</td>
<td>7.3</td>
</tr>
<tr>
<td>50</td>
<td>1.6</td>
<td>4.8</td>
<td>7.0</td>
</tr>
</tbody>
</table>

### 3.1.5.2. Sonication Time

Sonication time would be another feature which might make an impact on thermal conductivity of nanofluids. This parameter has been investigated by testing some samples prepared during different sonication times, i.e. 20 minutes, 40 minutes and 60 minutes. Six samples were available to study effect of sonication time on thermal conductivity of nanofluids which are tabulated as follow.

### Table 3.7: Information of nanofluids for sonication time test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Basefluid</th>
<th>Basefluid concentration (wt%)</th>
<th>Nanoparticle</th>
<th>Particle Size (nm)</th>
<th>Particle Concentration (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DW</td>
<td>100</td>
<td>Al$_2$O$_3$</td>
<td>50</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>DW</td>
<td>100</td>
<td>Al$_2$O$_3$</td>
<td>110</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>DW+AFN</td>
<td>50/50</td>
<td>Al$_2$O$_3$</td>
<td>40</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>DW+AFN</td>
<td>50/50</td>
<td>Al$_2$O$_3$</td>
<td>150</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>DW+AFN</td>
<td>50/50</td>
<td>Al$_2$O$_3$</td>
<td>250</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>DW+AFN</td>
<td>50/50</td>
<td>Al$_2$O$_3$</td>
<td>800</td>
<td>9</td>
</tr>
</tbody>
</table>

Figure 3.32 depicts thermal conductivity versus sonication time of water-based samples with Al$_2$O$_3$ (9 wt%) particles inside in 2 different sizes. It can be observed that increasing sonication time would result in increment in thermal conductivity of nanofluid.
Furthermore, distilled water/antifrog based nanofluids have been considered and thermal conductivity versus sonication time graph of them has been displayed in Figure 3.33. Mentioned conclusion regarding effect of sonication time on thermal conductivity of nanofluids has been confirmed by testing these new samples.

![Effect of Sonication Time on Thermal Conductivity](image)

**Figure 3.33: Thermal conductivity of DW+AFN/Al₂O₃ (9 wt%) for different times of sonication**

### 3.1.5.3. Particle size

Particle size of the nanofluid is another parameter which has been stated as effective one on their thermal conductivity. To investigate the role of particle size, some samples with same basefluid and particle type and various particle sizes have been examined. Figure 3.34 (right) and Figure 3.35 are considering thermal conductivity of samples number 3,4,5 and 6 from Table 3.7. It can be observed that increasing particle size from 40 nm to 250 nm would decrease thermal conductivity of nanofluid which was predictable based on literature. However, when the size of nanoparticles is 800 nm, thermal conductivity would increase extremely that it might be on account of agglomeration of particles at this big size.

It should be mentioned that same measurements have been done for water-based nanofluid with Al₂O₃ particles in two different sizes consisting of 50 and 100 nanometer. Data from measurement shows similar trend for nanofluid as before, i.e. bigger size of particle goes to lower thermal conductivity of nanofluids (Figure 3.34 (left)).
Figure 3.34: Thermal conductivity of and DW / Al₂O₃ (9 wt%) (left) and DW+AFN / Al₂O₃ (9 wt%)(right) at T=20°C for different particles sizes

Figure 3.35: Behavior of thermal conductivity of AFN/ Al₂O₃ (9 wt%) at T=20°C for different particle sizes

3.1.5.4. Particle Shape

It has been mentioned in literature review section that Murshed et al. investigated the effect of particle shape on thermal conductivity of nanofluids and reported higher thermal conductivity for nanofluids with rod-shaped particles rather than spherical shape [20]. Additionally, several researchers studied effect of nanoparticles on thermal conductivity of nanofluids. Researchers of Nanohex project also inspected the
effect of shape on thermal conductivity by examining Ag nanoparticles inside the mixture of distilled water and ethylene glycol with concentration of 50 weight percentage for each. Two different particles, including spherical shape and fiber-shaped silver nanoparticles were selected for this test. Based on measurement result, fiber-shaped nanoparticles can enhance thermal conductivity more than spherical shape nanoparticles and it can be observed in Figure 3.36.

![Effect of Particle Shape on Thermal Conductivity](image)

*Figure 3.36: Thermal conductivity of DW+EG/Ag (2 wt%) nanofluids at different temperatures*

Thermal conductivity enhancement of these two nanofluids in comparison with basefluid is tabulated below.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Spherical Shape</th>
<th>Fiber-Shaped</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.1</td>
<td>18.5</td>
</tr>
<tr>
<td>30</td>
<td>6</td>
<td>17.5</td>
</tr>
<tr>
<td>40</td>
<td>6.6</td>
<td>14.2</td>
</tr>
<tr>
<td>50</td>
<td>5.7</td>
<td>15.4</td>
</tr>
</tbody>
</table>

It should be noted that particle concentration of silver nanofluid in both samples is 2 weight percentage, therefore, from heat transfer point of view fiber-shaped nanoparticle would be much better choice since they can show 14 to 18 percent increment in thermal conductivity. However, it will be discussed that other properties such as viscosity and stability should be taken into account as well in order to evaluate probable applicability of nanofluids.

### 3.1.5.5. Alcohol

To evaluate effect of alcohol on thermal conductivity, some tests were run. The initial test was measuring thermal conductivity of basefluids which is mixture of alcohol and deionized water. Various proportions of ethanol (EtOH) was added to water which can be listed as below:

- Deionized water
- 95 volume percentage of deionized water and 5 volume percentage of ethanol
- 90 volume percentage of deionized water and 10 volume percentage of ethanol
- 85 volume percentage of deionized water and 15 volume percentage of ethanol
- 80 volume percentage of deionized water and 20 volume percentage of ethanol

The result of the thermal conductivity measurement has been depicted in Figure 3.37. In this graph, measured values for thermal conductivity of basefluids with ethanol have been compared with thermal conductivity of deionized water. Obviously, it can be comprehended that adding ethanol will cause subtraction of thermal conductivity of deionized water.

![Figure 3.37: Thermal conductivity of different mixtures of DI+EtOH at T=20°C](image)

Afterwards, thermal conductivity of nanofluids, which was synthesized by adding Al₂O₃ (with concentration of 3 weight percentage) nanoparticle to all five basefluids, was measured. Figure 3.38 shows comparative study of measured data for nanofluid; as long as, adding ethanol will decrease thermal conductivity of basefluid, same behavior takes place for nanofluid. It can be finally concluded that ethanol might not be good idea to be utilized in nanofluids; inasmuch as, it decreases thermal conductivity of basefluid, drastically.
Figure 3.38: Thermal conductivity of different mixtures of DI+EtOH with Al₂O₃ (3 wt%) nanoparticles inside at T=20°C

In addition, increment of thermal conductivity of nanofluid in comparison with basefluid when sample is at 20°C would be more or less same for all, i.e. between 1 to 2 percent. The data can be seen in Table 3.9.

<table>
<thead>
<tr>
<th>Material</th>
<th>Th. Conductivity (W/m.k)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI+Al₂O₃ (3 wt%)</td>
<td>0.595572115</td>
<td>1.6</td>
</tr>
<tr>
<td>DI+EtOH (95/5 Vol%)/Al₂O₃ (3 wt%)</td>
<td>0.572268043</td>
<td>1.7</td>
</tr>
<tr>
<td>DI+EtOH (90/10 Vol%)/Al₂O₃ (3 wt%)</td>
<td>0.554436435</td>
<td>1.2</td>
</tr>
<tr>
<td>DI+EtOH (85/15 Vol%)/Al₂O₃ (3 wt%)</td>
<td>0.532368139</td>
<td>1.2</td>
</tr>
<tr>
<td>DI+EtOH (80/20 Vol%)/Al₂O₃ (3 wt%)</td>
<td>0.507406066</td>
<td>1.2</td>
</tr>
</tbody>
</table>

3.1.5.6. Temperature

The last but not the least is temperature, which influences on thermal conductivity. This fact could be observed within all depicted figures above showing thermal conductivity of any nanofluid by changing temperature. Plainly, it can be declared that thermal conductivity of different nanofluids will increase by temperature increment.

Figure 3.39 illustrates thermal conductivity measurement of some water-based nanofluids composing TiO₂, Al₂O₃, ZrO₂ and CeO₂ nanoparticles with 9% by weight. Increase in thermal conductivity compared to water has been tabulated as well. Regarding Table 3.10, Titanium oxide (TiO₂) indicated highest value of thermal conductivity among these four samples.
3.1.5.7. Importance of synthesis

Within investigating different effective parameters on thermal conductivity of nanofluids, result of thermal conductivity increment in percentage has been discussed. Nanofluids are supposed to contain higher thermal conductivity in comparison with their basefluids. This issue is strongly depended upon preparation and synthesis phase of the nanofluid. One who is going to prepare nanofluid should take into account several features such as viscosity, stability, thermal conductivity and so forth.

Various types of nanofluid have been investigated at KTH laboratory and thermal conductivity of them has been measured while increase in thermal conductivity was anticipated. However, some of them did not show special increment in nanofluids while few of them indicated acceptable increase in thermal conductivity such as silver nanofluid with fiber-shaped particles, which was mentioned in section 3.1.5.5. SiC nanofluids are other group of samples prepared by some partners of Nanohex project and each of them showed different outcomes of thermal conductivity. Table 3.11 is including information of each sample in detail.
Table 3.11: Information of SiC nanofluids and their basefluids

<table>
<thead>
<tr>
<th>Base Fluid</th>
<th>Particles</th>
<th>W%</th>
<th>Powder Supplier</th>
<th>Synthesis by</th>
<th>1st Delivered to</th>
<th>2nd Delivered to</th>
<th>ID in the Graphs</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG/DW (50%V)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>KTH</td>
<td>KTH</td>
<td>-</td>
<td>KTH-EG/DW (53%W)</td>
<td>Pure EG</td>
</tr>
<tr>
<td>EG/DW (50%W)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Nanogap</td>
<td>KTH</td>
<td>-</td>
<td>NGP-EG/DW (50%W)</td>
<td>Pure EG</td>
</tr>
<tr>
<td>EG/DW (50%W)</td>
<td>SIC</td>
<td>9</td>
<td>ENEA</td>
<td>CPI</td>
<td>UTwente</td>
<td>KTH</td>
<td>CPI-UTwente</td>
<td>Pure EG</td>
</tr>
<tr>
<td>EG/DW (50%W)</td>
<td>SIC</td>
<td>9</td>
<td>ENEA</td>
<td>CPI</td>
<td>UBHAM</td>
<td>KTH</td>
<td>CPI-UBHAM</td>
<td>Pure EG</td>
</tr>
<tr>
<td>EG/DW (50%W)</td>
<td>SIC</td>
<td>9</td>
<td>ENEA</td>
<td>UBHAM</td>
<td>UBHAM</td>
<td>KTH</td>
<td>UHAM-UBHAM</td>
<td>Pure EG</td>
</tr>
<tr>
<td>DW - - - - - -</td>
<td>KTH-DW</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.40 illustrates result for thermal conductivity measurement of EG/DW-based nanofluids in different temperatures. Furthermore, Table 3.12 includes increment of thermal conductivity for three samples. It should be mentioned that sample with id of CPI-UTwente possesses highest value of thermal conductivity increment, which is around 50 percent. Yet, sample with UBHAM-UBHAM id showed only around 8 percent increase in thermal conductivity compared to basefluid. It must be mentioned that the sample CPI-UTwente leaked during the shipment to UTwente and might lost a lot of basefluid during the shipment. Therefore, the uncertainty of this increase is too high.

Figure 3.40: Thermal conductivity of SiC nanofluids at different temperatures
**Table 3.12: Thermal conductivity enhancement of SiC nanofluids compared to basefluid**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>CPI-UTwente (%)</th>
<th>CPI-UBHAM (%)</th>
<th>UBHAM-UBHAM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>47.2</td>
<td>16.8</td>
<td>6.95</td>
</tr>
<tr>
<td>30.00</td>
<td>53.7</td>
<td>19.7</td>
<td>8.22</td>
</tr>
<tr>
<td>40.00</td>
<td>52.6</td>
<td>18.0</td>
<td>8.06</td>
</tr>
<tr>
<td>50.00</td>
<td>50.9</td>
<td>16.7</td>
<td>8.36</td>
</tr>
</tbody>
</table>

To make the confirmation, test was repeated for each sample 15 times at T=20°C. On top of that, 5-minute delay was considered between two measurements to reach the equilibrium condition. Figure 3.41 shows the result of confirmation test.

![Thermal Conductivity at T=20 °C](image)

*Figure 3.41: Confirmation test of thermal conductivity for SiC nanofluids at T=20°C*

Consequently, result of this section can reveal importance of synthesis and preparation phase of nanofluids since nanoparticles with same elements can show different behavior.
4. Viscosity Measurement

In this section, rotating cylinder method has been applied to measure viscosity of some nanofluids and study effective parameters on their viscosity as well. It should be noted that instrument calibration and bath performance was performed in early stage.

4.1. Experimental result for viscosity

Viscosity of different kinds of basefluid and nanofluid are measured in the Lab using available viscometer. A brief description about instrumentation used for measurements, process of calibration for the viscometer, bath performance and measurement of different Nanofluids are presented.

4.1.1. Rotating cylinder method (Brookfield DV-II+ Pro viscometer)

The viscosity measurements are done using the Brookfield Engineering Labs Co. viscometer that offers different kinds of rotational ones; such as Coaxial cylinder, Cone plate and Cone cylinder viscometers. Brookfield DV-II+ Pro viscometer is a coaxial-cylinder one which operates based on measuring the rate of solid cylinder shape (Bob/Spindle) rotation in the viscous liquid sample.

A known force/torque proportion to viscous drag of the fluid against the spindle is measured by spring deflection measured by using rotary transducer. The torque needs to rotate the cylindrical shape medium (Bob/Spindle) inside the sample at angular viscosity and it will be the base of operation for this collection. Since it is been mentioned, the basic theory behind this kind of viscometers can be described by the Figure 4.1 and formulation (for Newtonian fluid) is extracted as below:

\[ M = \frac{4\pi r_1^2 r_2^2 \mu \Omega}{r_2^2 - r_1^2} \]  

(4.1)

As it can be seen from the Figure 4.1; \( r_1 \) is radius and \( h \) is height of the spindle inside the sample, \( r_2 \) is radius of sample holder/cup. The spindle has a constant speed (\( \Omega \) rad/sec) and the M (torque) is measured using the spring deflection and rotary transducer. The equation can be simplified as \( C \mu \Omega \) where \( C \) is a constant specific to the instrument.

Brookfield DV-II+ Pro Programmable Viscometer is the one used in the Lab for measuring viscosity. The DV-II+Pro provides exceptional opportunity in terms of control allowing for traditional standalone operation, automatic operation is done by means of Brookfield Rheocalc32 Software. The Brookfield
Rheocalc32 Software has a high capability to control the system. In addition, it is capable to collect data and provide a platform for advanced data analysis.

4.1.1.1. The procedure

To start working with the viscometer some steps should be taken as following:

- **Initial leveling of the viscometer**: Using the leveling screws since the viscometer should be leveled initially.
- **External mode selection**: This action will connect the DV-II+Pro externally to the PC and Rheocalc32 Software.
- **Auto-zero procedure**: After removing the spindle, the auto zero procedure should be done. The connection bolt on the DV-II+Pro starts to rotate for approximately 15 seconds. After auto zero procedure, software displays the torque in percentage which should be below ±1% in order to run the measurement. If it was beyond the range (±1% torque), leveling of the viscometer is required.
- **Spindle Selection**: LVDV-II+Pro Viscometers are provided four different spindles in addition to ULA. Regarding the sample different spindles might be selected.

![Different Spindle models](image)

**Figure 4.2: Different Spindle models**

<table>
<thead>
<tr>
<th>LV Spindle</th>
<th>Viscosity range cP(mPa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV-1</td>
<td>15-20000</td>
</tr>
<tr>
<td>LV-2</td>
<td>50-100000</td>
</tr>
<tr>
<td>LV-3</td>
<td>200-400000</td>
</tr>
<tr>
<td>LV-4</td>
<td>1000-2000000</td>
</tr>
</tbody>
</table>

**Table 4.1: Different Spindle models [120]**
Speed Selection, Setting and Running: Finally, regarding two important considerations (torque range and turbulent criterion) speed range can be set and program will be run.

4.1.1.2. Brookfiled DV-II+ Pro viscometer characteristics

In the Figure 4.3, schematic diagram showing different parts of the experimental setup for the viscosity measurement is illustrated. The whole measurement system includes Brookfield DV-II+Pro Viscometer, UL adapter (ULA/ rotating coaxial cylinder), Bob/Spindle, cooling Jacket, cooling Bath, computer processor with Rheocalc32 Software.

![Figure 4.3: Schematic diagram of DV-II+Pro and components](image)

![Figure 4.4: Different parts of DV-II+Pro viscometer](image)
The Brookfield Laboratory Viscometer (DV-II+Pro) displayed in Figure 4.4 above, consists of a stand with two leveling screws, sample holder and cooling jacket (Figure 4.6) connected to the DV-II+Pro by an aluminum frame and stainless spindle /bob (Figure 4.5). DV-II+Pro is connected to the PC which processes and displays data such as Viscosity (cp/m.ps), Speed (rpm), Torque (%), Shear Stress, Shear Rate, Temperature, Time Interval, Date & Time and Spindle type. The viscometer can be used both manually and automatically.

Most of viscosity measurements are executed by ULA sample holder and spindle. Some characteristics of viscometer of the DV-II+Pro are listed in the Table 4.2.

<table>
<thead>
<tr>
<th>Model</th>
<th>Spring Torque (milli N/m)</th>
<th>Number of Spindles</th>
<th>Speed range (rpm)</th>
<th>Gross Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV-II+Pro</td>
<td>0.0673</td>
<td>4 &amp; 1 ULA</td>
<td>0.1 - 200</td>
<td>10.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature Sensing Range (°C)</th>
<th>Viscosity Accuracy</th>
<th>Viscosity Repeatability</th>
<th>Temperature Accuracy (°C)</th>
<th>Operating Environment (Temp. °C &amp; R.H %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100 to 300</td>
<td>±1.0% of full scale range</td>
<td>±0.2%</td>
<td>±1°C (-100 to +149)</td>
<td>0 to 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±2</td>
<td>20% to 80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(+150 to +300)</td>
<td></td>
</tr>
</tbody>
</table>

The full-scale viscosity range for any DV-II+Pro model and spindle may be calculated using the equation below:

$$\mu = TK \times SMC \times \frac{10000}{RPM}$$  \hspace{1cm} (4.2)
where,

TK : DV-II+Pro Torque Constant Code of Viscometer

SMC : Spindle Multiplier Constant Code of Viscometer

4.1.1.3. Two important considerations:

Regarding Brookfield Eng. Lab. report, there are two considerations which should be met so as to have proper and high precision viscosity measurements with the DV-II+Pro. These conditions affect the viscosity measurement.

4.1.1.3.1. Torque consideration

Torque consideration has something to do with the accuracy and high precision measurement. Viscosity measurements are acceptable within the equivalent Torque Range from 10% to 100% for any combination of spindle/speed rotation. The torque percentage is function of fluid viscosity and angular viscosity of the spindle. Besides, Newtonian and non-Newtonian behavior of the fluid can also affect the torque percentage and measurement constraints.

Since the viscosity of sample influence on the range of measurement (searing the fluid), the temperature selected and set on the cooling bath will affect the torque range.

This range by selecting a higher temperature for viscosity measurement may increase or sometimes decrease the range of shearing. On the other hand, selecting a lower temperature for viscosity measurement may also lead to the same result – increment of torque range. e.g. for low-viscous fluids like water, the range is limit and will be restricted more by rising the temperature.

To measure the viscosity of different fluids this range will differ. Therefore, currently the method for speed selection is trial and error so that we have a measurement in the torque range which company has suggested. Since the researchers in this filed are interested in shearing the flow in a large range, torque range may completely limit the measurement. Another solution to develop the measurement range is using various types of spindle.

However, there are some liquid samples which cannot be measured in this range. Although company suggested to follow this range in the measurements, it is possible to measure in lower than 10% torque with more measurement point and average technique to have better accuracy close to the recommended range. Since it is been mentioned, there is a trial by error method to find the range. What was used in the KTH Lab was an initial test to set the program and share the sample as much as possible to have better understanding of fluid behavior. On the other hand, it would be possible to define a standard for such instrument so that there is no need to try and error method for the speed selection range.

4.1.1.3.2. Turbulent criterion

In addition to the former consideration, the measurement should be investigated from fluid mechanics point of view. From rheological perspective, viscosity measurements should be taken under laminar flow conditions rather than turbulent flow.

Within measurement under laminar fluid flow, the viscosity is pure resistance of flow shearing around the spindle. On the other hand, when there is higher internal flow forces the particles inside the flow and around the spindle will have a random movement (turbulent flow) rather than a circumferential one.
Thus, the flow behavior would not be considered as a simple model and make a non-linear viscosity increment by angular velocity increment—the viscosity measured is partially due to turbulent flow not the real viscosity of flow. For the UL Adapter, the criterion to avoid turbulent flow is defined experimentally by the company as a ratio of rpm to viscosity (cP). They have found that the transition point to turbulent flow for ULA occurs if there is 0.85 cP at 60 rpm. They have also suggested the ratio to apply in the measurements, i.e. turbulent conditions will happen whenever the rpm/cP ratio exceeds the values 60/0.85 (~70.5). For this consideration a try and error is also needed and no standard provided. To set a program and run the viscometer, the initial test to have an estimation of viscosity was done. Afterward, based on this criterion and torque consideration the measurements were done.

4.1.2. Instrument Calibration

The calibration process is verification for the instrument. Instrument calibration is an important issue in any measurement and is a primary processes used to check the instrument accuracy.

The accuracy of the DV-II+Pro is defined using the standard fluid which Brookfield engineering Lab provided. Since the standard fluid provided to calibrate the viscometer is Newtonian, spindle speed is not a significant issue. As the standard fluids are measured at 25 °C, the temperature of bath should set at the same temperature. Then, after a period of time (15 min), when the test fluid gets same temperature, the measurement of standard flow can be performed.

Moreover, in the KTH Lab, DV-II+Pro is calibrated using some other basefluids with known viscosity like DW, EG and their mixture (50 vol%). As it was mentioned earlier, the measurements of viscosity are done by running a program on the viscometer software. In order to measure viscosity with highest possible accuracy in the calibration test, a special kind of program was set in which viscosity in each temperature is measured at more than 600 sample points in different shear rates. Afterwards, the average of these measurements in each temperature is selected as viscosity of the sample. It should be noted that this kind of average method is possible for fluids which are Newtonian (to get an average of viscosity in different shear rates as the viscosity is constant). It is possible to measure the viscosity of non-Newtonian fluids using this method; however, it can be done for a constant shear rate (in each shear rate separately) and average method for different shear rates is meaningless.

The calibration of viscometer is done by water at temperatures of 20 °C, 30 °C, 40 °C, 50 °C and 60 °C. Water was selected as a low-viscous fluid to confirm the accuracy of instrument in low viscosity measurement. As it can be seen in the Figure 4.7, the viscosity of DW versus temperature is illustrated and compared with some databases (references) like NIST [159], DDBST [125], Efenda [121] and L.Corson et al. [122]. The viscosity measurements at KTH almost follow all databases especially NIST database. Moreover, the deviation of measurements from NIST data (±5%) are shown in the graph as well. Therefore, each point in viscosity measurement shown in the Figure 4.8 is around 700 experiments in a time interval.
Concerning Figure 4.7 and Figure 4.8, result for distilled water had an acceptable deviation from the references used to be compared with especially NIST database. The deviation for DW at 20 °C in average is 2.5% from the other measured values and around 3% from NIST data which is a very good validation for the viscometer at T=20 °C. The same story happens for the 30 °C in which the deviation of KTH measurement is 2.25% and around 3% from average and NIST data respectively.

The water viscosity is deviated around 4, 2.5 and 1 from the average viscosity of references at 40 °C, 50 °C and 60 °C, respectively. Regarding the NIST data, the deviation seems similar.

Based on viscosity of DW measured as a low-viscous fluid by DV-II+Pro and deviation of measurements from mean value of acceptable references in Figure 4.7, a good confirmation of instrument for low-
viscous fluid is achieved. Consequently, based on average viscosity of different references brought, it can be understood that the viscometer shows viscosity of samples somehow higher.

![Image 1](https://via.placeholder.com/150)

**Figure 4.9: Average deviation of distilled water viscosity measurement at KTH from different databases**

Another sample selected to evaluate the validity and accuracy of viscometer was EG. Since the viscosity ratio of EG and water is relatively high, this measurement could be a proper calibration for the instrument at high viscosity measurement.

![Image 2](https://via.placeholder.com/150)

**Figure 4.10: Viscosity of EG for different databases compared KTH measurement**

66
The calibration of viscometer is done at different temperatures by EG. To achieve the highest possible accuracy in measurements same program was set in Rheocalc32 Software and same strategy was chosen-Sampling of many points and average technique. Figure 4.10 shows viscosity of EG versus temperature for different references compared to KTH measurement. Åke Melinder (2011) [123], Waterloo Uni. Database(Microelectronics Heat Transfer Laboratory) [124], DDBST [125], Landauer O. et al. [127] and other references show that the measurements at KTH follow their values for viscosity of EG at different temperatures (20-60 °C).

The Figure 4.11 also shows the percentage of deviation versus temperature of KTH measurement compared to all databases and articles. As it has been illustrated, the highest deviation occurs for the viscosity measurement compared to Å. Melinder database at 20 °C, 40 °C and 60 °C. However, the deviation is almost below 10%. Waterloo Uni. Database confirms less than 5% deviation for viscosity of EG in all temperature except 60 °C. The same scenario can be seen in Figure 4.11 for the DDBST in which the variation of KTH measurements are less than 1% at temperatures 20 °C and 30 °C and less than 5% for the other temperatures. The EG viscosity follows the Corradini F. et al. [126] measurements which shows less than almost 3% divergence at all temperatures.

Moreover, Technische Hochschule Carl Schorlemmer [130], Yang C. et al. [129] and Estel E. et al. [128] measurements are less than 3% deviated from the KTH measurements except 60 °C in which the deviation is still lower than 5%. Kozin et al.[131] also measured viscosity of EG which confirms KTH measurements.

![Figure 4.11: Deviation of KTH measurement (EG) for distilled water from different data bases](image)

Figure 4.11 shows the average deviation of KTH viscosity measurement of EG from different databases. The figure illustrate less than 5% deviation from different references up to 50 °C, i.e. 3% at 20 °C, 2% at 30 °C, around 4% at 40 °C and 50 °C. The greatest deviation is relating sample at 60 °C. Based on average
differences of viscosities, it can be concluded that the viscometer is validated enough for measuring fluids with higher viscosities than water.

![Average Error of References from KTH Measurement (%)](image)

*Figure 4.12: Average deviation of KTH viscosity measurement (EG) from different databases*

The third liquid used for the calibration of the viscometer was DW+EG (50 vol%). Figure 4.13 illustrate the viscosity of DW+EG (50 vol%) (cP) versus temperature. The only reference used to compare the measurements is ASHRAE [161] and as it can be seen, the test results have a good agreement with ASHRAE database. The graph shows a confirmation of ±10 deviation for measurements. The deviation for temperatures from 20 °C to 50 °C are 7, 5, 8 and 10% difference, respectively. Generally, it can similarly be seen a higher viscosity record by the DV-II+Pro viscometer; however, it is almost a good confirmation for the instrument and measurements.

![Viscosity- DW+EG (50 vol%)](image)

*Figure 4.13: Viscosity of EG/DW (50 vol%) for different data bases compared KTH measurement*
4.1.3. Thermal Bath performance of Viscometer

One of the most economical depended issues in nanofluids and any kind of cooling fluids is viscosity, since it is directly connected to pumping power. The viscosity is a property which is highly temperature dependent. Thus, accuracy of measurements done by Brookfield DV-II+ Pro can be viewed critically from this angle and there is a need to investigate more through this issue.

As it was shown in the Figure 4.3, the viscometer is comprised of different parts. Cooling bath and double jacket cooling used to make an equilibrium temperature for the system during measurements are two important parts. Thus, it is aimed to have a bath and double jacket cooling performance so as to prove if the system is capable to maintain the temperature constant during measurement.

In this consideration, seven calibrated thermocouples are selected to do the bath performance. Two thermocouples put into the bath to check the bath temperature, 3 thermocouples attached to the spindle wall and two others to the bottom and head of it (Figure 4.14). As it can be seen in the Figure 4.14, the thermocouples are attached on the spindle equally (distance of thermocouples from each other is around 2.5 cm).

Thermocouples 1 and 5 are attached respectively to the bottom and top of the Spindle to check the temperature of those positions. The other three (No. 2, 3 and 4) are around the cylinder whose temperature is very important. Since the most effective surface in contact with fluid is around the spindle, i.e. viscosity calculation will mostly be affected by this area. Therefore, it was tried to have a more precise look to this part of spindle/sample holder. Given the first point of soldering connection in thermocouples (made by hand) record temperature, it was tried to attach the thermocouples properly on the spindle.

Three conditions are presumed for this measurement:

- The measurements are done while the spindle was steady and there was no rotation. It is assumed that the temperatures around, above and bottom of spindle are mostly same as real measurement while the viscometer is running and spindle is rotating-there was not sufficient space and also possibility using the current system measure temperature during viscosity measurement. However, it seems while system is running and viscometer is measuring, there would be a better condition of flow mixing and proper temperature distribution. The only thing would be higher risk of heat loss due to flow motion other than stationery condition.

- Water assumed good enough to do the test. The standard of company for sample which is supposed to be measured is 16 ml. Since there are some volumes extra, to get close to real condition, 14 ml water put into the sample holder-the level of sample inside the sample holder would affect the temperature of TCs’ location.

- Environment temperature is almost constant during the test. It was around 24 °C in all measurements.

Different temperatures from 20 °C up to 60 °C are investigated through this study and the result will be presented in the next session.
First consideration is at temperature of 20 °C which is almost below environment temperature. Figure 4.15 shows the variation of temperature inside the bath and sample holder versus time. As it is illustrated in this figure, there is a severe fluctuation for one of thermocouples in the bath between 14 to 19 degree Celsius, which is probably located close to the bath pump, and it is not included in the calculations. Besides, another thermocouple has rather a smooth behavior in the time interval and is mostly close to the set point. For the other thermocouples attached on the spindle, there is a good agreement of all thermocouples especially those which are around the spindle. Thermocouple No. 1 shows around 1 °C difference from the other ones attached on the spindle which would be due to environment temperature effect.

Figure 4.16 also shows an average temperature of thermocouples inside the bath and double cooling jacket. An average value was made for thermocouples 2, 3 and 4 around the spindle and thermocouple 1 inside the bath was selected as representative of bath temperature. The reason behind selecting only three thermocouples inside the sample holder (attached to the spindle’s wall) was that around the cylinder shape spindle is the most important part to calculate viscosity of sample (the effective surface in viscosity
Importantly, all temperatures measured inside the sample holder may have a better uniformity with each other during the measurement as the spindle is rotating and fluid flow makes this uniformity easier. Obviously, the average temperature for the sample holder is close enough to adjust temperature (20.17 °C). The difference calculated and was less than 1%. The average temperature for bath is about 19.7 °C to meet the 20 °C adjusted temperature in the sample holder. The bath temperature difference (0.3 °C) probably comes back to the environment temperature which is higher than adjusted temperature. The TC-502 Temperature Control Bath connecting to sample holder try to set itself in a lower temperature to fulfill the temperature 20 °C in sample holder and compensate the heat flow from the environment to the system.

![Average Value/cooling Jacket, Set Point=20°C](image)

*Figure 4.16: Bath performance average temperatures for viscometer at T=20 °C*

Revealing the importance of bath performance during temperature change, temperature of bath has changed from 20 °C to 30 °C. As it can be found from the Figure 4.17, bath temperature meets the set point after about 3 minutes while the thermocouples 1 at the bottom and 5 at the top of sample holder reach to the set point for about 14 minutes. For the other points (around the spindle), the time range is between 3 and 14 minutes. Secondly, it can be easily understood from Figure 4.17 that around 14 minutes is required to reach stable temperature in the sample holder to launch the measurement. This time may differ based on set point adjusted on the bath. Since the average environment temperature during temperature monitoring is less than environment temperature, except bath temperatures, the sample holder thermocouples show environment interference and are less than 30 °C. Even after 15 minutes, the thermocouple 1 cannot reach to the set point.

The result of temperature monitoring for the other adjusted temperatures (40 °C to 60 °C) are in the Appendix B.
Figure 4.17: Bath performance for viscometer from temperature of 20°C to 30°C

Figure 4.18 also illustrates temperature monitoring of bath and sample holder versus time at 30°C. The figure shows how the temperature graphs in both bath and sample holder follow the set point. Although there is a small upward tendency for temperature, it still seems proper stability for measurements at 30°C. Due to lower temperature in environment, thermocouple 5 connected to the bottom part of spindle again shows lower temperature than the set point.

Figure 4.19 also shows an average temperature of thermocouples inside the bath and double cooling jacket. At 30 °C, since the thermocouples 6 and 7 inside the bath had reasonable fluctuations, an average value was computed for thermocouples inside the bath and around the spindle. Average temperature for thermocouples attached around the spindle have a very good agreement with adjusted temperature (29.9 °C). A 0.3% difference between adjust and average temperature was calculated. The average temperature
for bath is higher than set point in this case. This issue again comes back to the ambient temperature which is lower than adjusted temperature. The TC-502 Temperature Control Bath connecting to sample holder try to set itself in a higher temperature to compensate the heat losses in fluid circulation and other steps.

Based on Table 4.3, it can be found that highest deviation from the adjusted temperature is relating to the 60 °C and the lowest one in related to the 30 °C. As it is illustrated in Figure 4.20, the deviation of temperatures from 20 °C to 60 °C is almost linear and completely affected by the environment temperature. As the set point temperature increases, the temperature difference from the environment gets higher. Consequently, it is more difficult for the bath to make the temperature uniform and close to the set point - higher heat loss contributed to this issue. The differences in temperature for set points 20 to 60°C are 0.85, 0.23, 0.64, 2.2, 2.7 %, respectively.

Regarding bath performance results, an important outcome can be expressed. Although the results of calibration tests confirmed the performance of viscometer (almost below 5% error for DW and EG compared to the data bases), the higher recorded viscosities for basefluids (DW, EG and DW/EG 50 vol%) specially at higher temperatures (except 20 which is lower than environment temperature) are attributed to this temperature differences.

Since the viscosity increases by decreasing the temperature and the temperature of sample inside the sample holder is less than the set point, it is expected to observe higher viscosity. The solution which can be suggested is to use insulation around double jacket cooling and put a lid on top of sample holder. It will probably decrease the heat losses and even evaporation of sample so that a higher accuracy can be achieved. The effect of insulation and lid on the viscosity measurement would be investigated in the future studies (Temperature monitoring of viscometer with additional insulation).

### Figure 4.19: Bath performance average temperatures for viscometer at T=30 °C

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>t-Cylinder</th>
<th>t-Bath</th>
<th>t-Adjust</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average Value/cooling Jacket, Set Point=30°C
Figure 4.20: Bath performance, average deviation from the set point at different temperatures

Table 4.3: Bath performance, percentage of deviation from the set point at different temperatures

<table>
<thead>
<tr>
<th>Set point (°C)</th>
<th>Temperature Difference (°C)</th>
<th>Percentage of difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>0.17</td>
<td>0.85</td>
</tr>
<tr>
<td>30.00</td>
<td>0.07</td>
<td>0.23</td>
</tr>
<tr>
<td>40.00</td>
<td>0.64</td>
<td>1.6</td>
</tr>
<tr>
<td>50.00</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>60.00</td>
<td>1.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>
4.1.4. Experimental Studies on Viscosity of Nanofluids

In this session, firstly Newtonian and non-Newtonian behaviors of different nanofluids are studied. Afterwards, some of important factors affecting viscosity of nanofluids will be introduced and studied experimentally.

4.1.4.1. Different type of viscosity:

Regarding different apparent viscosities under different conditions there are basically two various kinds of fluid:

- Newtonian fluids

They are fluids whose viscosity is independent of shear rate or behavior of the stress versus strain rate graph is linear and it passes through the origin, e.g. water, EG and most gases which have a constant viscosity can be introduced as Newtonian fluids.

- Non Newtonian fluids:

They are fluids which exhibit a more complicated behavior and have different relation than simple linearity between shear stress and velocity gradient. In other words, the viscosity of fluid is function of shear rate.

Non-Newtonian fluids can be categorized into different genres as below:

- Shear thickening fluids whose viscosity increases with the rate of shear.
- Shear thinning is in contrast with shear thickening fluids and their viscosity decreases with the rate of shear.
- Thixotropics are materials whose viscosity is time dependent and become less viscous over time when shaken, agitated, or otherwise stressed.
- Rheopectics are fluids which behave differently from Thixotropic ones and become more viscous over time when shaken, agitated, or otherwise stressed.
- A Bingham plastic is also another kind of fluid which behaves as a solid at low stresses but flows as a viscous fluid at high stresses.

4.1.4.2. Measurement of some Newtonian and non-Newtonian Basefluids/Nanofluids

Figure 4.21 shows the viscosity of AFN/DW (50 wt%) based CeO$_2$ versus shear rate in different temperatures form $T=20^\circ$C to $T=60^\circ$C. Nanofluid is sheared from $10$ S$^{-1}$ to $215$ S$^{-1}$ in different temperatures considering the instrument restrictions.

By increasing the shear rate, the viscosity of nanofluid in different temperatures decreases. Since the viscosity of nanofluid decreases by increasing shear rate, the nanofluid is non-Newtonian and indicates shear thinning.
Figure 4.21: Viscosity of DW+AFN/CeO$_2$ (9 wt%) versus shear rate at different temperatures

Figure 4.22 also illustrates the measured shear stress as a function of shear rate for CeO$_2$ (9 wt%) in different temperatures form T= 20°C to T= 60°C. It can be seen in the chart that the shear rate depends non-linearly up on the shear stress (especially from 10 to 50 S$^{-1}$) and the viscosity is not a constant, indicating the non-Newtonian behavior of CeO$_2$ under the conditions of this work. However, since the nanofluid in different temperatures has a tendency to be almost constant regarding shear rate, the non-linearity of nanofluid may not be observed clearly.

Figure 4.22: Shear stress of DW+AFN/CeO$_2$ (9 wt%) versus shear rate at different temperatures
Figure 4.23 presents the viscosity of DEG based nanofluid containing Cu nanoparticles as function of shear rate at temperatures different temperatures. Since the viscosity of nanofluid is constant by increasing the shear rate, it can be understood that nanofluid is Newtonian.

![Figure 4.23: Viscosity of DEG/Cu (0.6 wt%) versus shear rate at different temperatures](image)

Moreover, Figure 4.24 shows the shear stress of DEG based Cu (6 wt%) measured versus shear rate in temperatures from 20 to 60 °C. It is clear that the shear rate depends linearly on the shear stress and the constant viscosity is indicating the Newtonian behavior of this nanofluid.

![Figure 4.24: Shear stress of DEG/Cu (0.6 wt%) versus shear rate at different temperatures](image)

In another investigation, shear stress of three types of DW/AFN based Al₂O₃ with different nanoparticle sizes (40, 150 and 250 nm) are measured at different shear rates. As it can be understood there is a linear
relation between shear rate and stress. Meanwhile, increasing the temperature is resulted in lower rate of shear stress increment.

4.1.4.3. Considering effective parameters on Viscosity:

As it was described earlier, most of researchers have agreed on some parameters which may influence on nanofluids viscosity. Parameters such as basefluid, nanoparticle, particle concentration, shape/size of particles, surfactants, sonication time and temperature reviewed in the literature and some of them are examined experimentally.

4.1.4.3.1. Particle concentration

Figure 4.26 shows viscosity of three AFN based nanofluids including CeO$_2$ (1, 2 and 3 wt%) nanoparticles versus temperature. At lower volume fraction (1wt%), nanofluids do not have almost low viscosity increment as corresponding basefluids due to lubricative effect of nanoparticles especially at T= 20 °C [132]. By increasing the weight percentage of CeO$_2$, the viscosity of nanofluids also raises.

Since behavior of theses nanofluids changed from Newtonian to non-Newtonian by increasing volume concentration and also temperature, to compare their viscosity of CeO$_2$ (1,2,3 wt%) same share rate is selected- for those temperatures and volume concentrations which showed non-Newtonian behavior. Shear rate selected to compare was 20.14 (1/s).

Figure 4.27 illustrates the behavior of viscosity increment for all three nanofluids and as it can be seen, the rate of increment for 2 and 3 wt% follow almost the same trend. Besides, augmentation of viscosity for 3 wt% in different temperatures is higher than the two others. The trend of viscosity increment versus temperature deviate from 1 and 2 wt% and reaches around 75% of AFN (basefluid).
Table 4.4 gives the exact values for the viscosity rising in different volume concentrations from temperature 20 to 60 °C. It can be concluded that the higher volume concentration of nanofluids, the larger viscosity they have. Moreover, changing the temperature, the viscosity difference among various weight percentages of CeO$_2$ is dissimilar.
Table 4.4: percentage of viscosity increment of AFN/CeO$_2$ 1, 2 and 3 wt% at different temperatures

<table>
<thead>
<tr>
<th>Material</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T=20 °C</td>
<td>T=30 °C</td>
<td>T=40 °C</td>
<td>T=50 °C</td>
<td>T=60 °C</td>
</tr>
<tr>
<td>AFN/CeO$_2$ (1 wt%)</td>
<td>0,58</td>
<td>5,58</td>
<td>4,34</td>
<td>6,66</td>
<td>18,78</td>
</tr>
<tr>
<td>AFN/ CeO$_2$ (2 wt%)</td>
<td>1,15</td>
<td>11,68</td>
<td>12,57</td>
<td>19,91</td>
<td>31,47</td>
</tr>
<tr>
<td>AFN/ CeO$_2$ (3 wt%)</td>
<td>17,31</td>
<td>29,25</td>
<td>39,78</td>
<td>54,54</td>
<td>75,86</td>
</tr>
</tbody>
</table>

Another study is considering effect of weight/volume concentration of particles on rheological behavior of nanofluids. Besides the effect of particle size on viscosity, it can be concluded that the particle size can also affect the rheological behavior of nanofluid from Newtonian to non-Newtonian, surprisingly.

Therefore, shear thinning/thickening can contribute in the nanofluid application. Figure 4.28 presents the viscosity of CeO$_2$ (1, 2 and 3 wt%) at T= 20 °C and 30 °C. It can be seen from the chart that the behavior of nanofluids at T= 20 °C for CeO$_2$ 1 wt% is Newtonian and independent of shear rate. By increasing the weight percentage from 1 to 2 wt% and 3 wt%, the behavior of nanofluids becomes shear rate dependent and non-Newtonian.

The behavior of these nanofluids (2 and 3 wt %) can be predicted using the power law model with its two fitting parameters:

$$\mu = K \gamma^{n-1} \quad (4.3)$$

Where $n$ is representing the power law index and $K$ is consistency index.

The power law index of nanofluids normally increases with an increase in temperature. Moreover, the consistency index of nanofluids decreases with temperature and increase with volume concentration.

Figure 4.28: Viscosity of AFN/CeO$_2$ 1, 2 and 3 wt% versus shear rate at two different temperatures
4.1.4.3.2. Shape of particles

Particle shape serves a strong role on the shear dependent behavior and also viscosity increment of nanofluids. Figure 4.29 displays the viscosity of DW/EG (50 wt %) based Sic nanofluids as the function of temperature. The only difference between the nanofluids is shape of particles. As it is depicted in the Figure 4.29, spherical type has a low viscosity increment due to lubricative effect of nanoparticles especially at higher temperatures [132]. On the other hand, nanofluid containing fiber shaped nanoparticles (Sic) proves higher viscosity. Table 4.29 also provides exact value of viscosity increment made by both spherical and fiber shaped nanoparticles. The viscosity of nanofluid containing spherical shape particles changes from almost 5 to 1.5% in temperature range of 20 to 50 °C. The fiber shaped nanofluid which showed higher viscosity, altered from 39 to 26% viscosity increment rather than the basefluid.

These two figures and Table 4.5 demonstrate effect of shape on the rheological behavior of nanofluids. Effect of nanoparticle shape cannot be seen only from viscosity angle, yet, thermal properties of nanofluid should also be taken into account.

![Effect of Shape on Viscosity of Nanofluid](image)

*Figure 4.29: Viscosity of DW+EG/Ag (2 wt%) nanofluids at different temperatures*

<table>
<thead>
<tr>
<th>Shape</th>
<th>Increment (%) T=20 °C</th>
<th>Increment (%) T=30 °C</th>
<th>Increment (%) T=40 °C</th>
<th>Increment (%) T=50 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Shaped</td>
<td>39,24</td>
<td>34,99</td>
<td>30,54</td>
<td>25,93</td>
</tr>
<tr>
<td>Spherical Shaped</td>
<td>5,02</td>
<td>4,84</td>
<td>2,96</td>
<td>1,44</td>
</tr>
</tbody>
</table>

*Table 4.5: percentage of viscosity increment of DW+EG/Ag (2 wt%) at different temperatures*
4.1.4.3.3. Size of particles

Since it was mentioned in advance, particle size of nanoparticle may also affect the viscosity of nanofluids. Figure 4.30 illustrates the viscosity of water-based Al$_2$O$_3$ 9 wt% (with nanoparticle size of 50 and 110 nm) versus shear rate (Table 3.7). Moreover, viscosity of DW is measured. As it is displayed in the graph, both nanofluid and basefluid have no dependency on shear rate, indicating Newtonian behavior for these samples. Water, Al$_2$O$_3$ (50 nm) and Al$_2$O$_3$ (110 nm) shared form 10 up to 90, 140 and 180 (1/S) regarding viscometer ability at 20 °C.

Average viscosity for nanofluid with a smaller nanoparticle is about 2.28 cP while the nanofluid with larger nanoparticles shows viscosity around 4.63 cP. From this result, it can be concluded that there is a viscosity increment raising the size of nanoparticle.

![Effect of Particle size on Viscosity of Water Based Al$_2$O$_3$](image)

Figure 4.30: Viscosity of DW/Al$_2$O$_3$ (9 wt%) versus shear rate at different temperatures

Figure 4.31 shows the viscosity of AFN/DW based nanofluids (Al$_2$O$_3$ 9 wt %) as a function of shear rate at 20 °C. Al$_2$O$_3$ with nanoparticle size of 40, 150 and 250 nm was measured and showed independent behavior of shear rate, as same as their basefluids, which demonstrates a Newtonian behavior for these bunches of nanofluids. Interestingly, by increasing size of nanoparticles from 250 to 800 nm, behavior of nanofluid changes and becomes into shear rate dependent, representing a Non-Newtonian behavior.

Moreover, Figure 4.31 presents the effect of particle size on apparent viscosity of the basefluid. Since it was listed in Table 3.7, nanofluids with four different nanoparticle sizes and same concentrations are examined. It is worth mentioning that the nanofluid including the nanoparticles with size of 800 nm showed Non-Newtonian behavior and as a result could not be represented as a single number. However, comparing Non-Newtonian nanofluid (800 nm particle size) with other ones, it is decided to compare in a specified shear rate (at shear rate of 71S$^{-1}$). As it can be observed, nanofluids’ viscosity decreases by increasing the size of nanoparticles up to 250 nm. However, the nanofluid containing 800 nm nanoparticles, which possesses shear-thinning behavior, shows higher viscosity than the other particle sizes. Concerning these results, an interesting conclusion can be taken that there would be an optimum size of particle for the viscosity of nanofluids. Table 4.6 also gives the exact value of viscosity increment which is 24, 39 and 59% for nanofluids containing 250, 150 and 40 nm particles and the viscosity rising for the nanofluid including 800 nm particles was 112%.
Besides effect of particle size on viscosity, surprisingly, it can be concluded that the particle size can also affect the rheological behavior of nanofluid from Newtonian to non-Newtonian behavior. Therefore, shear thinning/thickening can contribute in the nanofluid application.

Above all, the thermal properties of nanofluid should be taken into account besides aiming at optimizing the viscosity attributed to particle size. It may be found that the ratio of thermal conductivity to viscosity is higher for nanofluid, which has higher viscosity other than the one with least viscosity.

**Figure 4.31:** Viscosity of AFN+DW/Al₂O₃ (9 wt%) versus shear rate at T=20 °C

**Figure 4.32:** Viscosity of AFN+DW/Al₂O₃ (9 wt%) for different particle size at T=20 °C
Table 4.6: percentage of viscosity increment of AFN+DW/Al₂O₃ (9 wt%) for different particle size at T=20 °C

<table>
<thead>
<tr>
<th>Material</th>
<th>Average Viscosity (Cp)</th>
<th>Nanoparticle size (%)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW+AFN (50 wt%)</td>
<td>4.27</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃</td>
<td>6.79</td>
<td>40</td>
<td>59</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃</td>
<td>5.94</td>
<td>150</td>
<td>39</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃</td>
<td>5.30</td>
<td>250</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Viscosity (Cp)</th>
<th>Nanoparticle size (nm)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW+AFN/Al₂O₃</td>
<td>9.07</td>
<td>800</td>
<td>112</td>
</tr>
</tbody>
</table>

Developing the investigation concerning particle size influence on viscosity, former nanofluid (AFN/DW based Al₂O₃ 9 wt %) were measured at higher temperatures. In Figure 4.33, viscosity of DW/AFN based Al₂O₃ containing nanoparticles with different sizes (40, 150 and 250 nm) versus temperature are measured. As it can be seen in the graph, increasing the size of nanoparticles lead to lower viscosity for nanofluid in all temperatures.

Moreover, Figure 4.34 illustrates the percentage of viscosity increment for nanofluids with different nanoparticle sizes. As it can be seen, the increment for Al₂O₃ containing 40 nm particle size was about 50% at temperature of 30 °C and about 47% at 40 °C and 50 °C. Nanofluid with particle size of 150 nm showed 40, 35 and 33% increment at temperature of 30 °C, 40 °C and 50 °C, respectively. In addition, nanofluid with size of 250 nm, which possesses lowest amount of viscosity rise, showed 23, 19 and 14 percent increment at temperatures 30°C, 40°C and 50°C, respectively.

![Effect of Particle size on Viscosity](image-url)
In this section, effect of EtOH on both basefluid and nanofluid will be investigated experimentally. Figure 4.35 illustrates the viscosity of DI/EtOH in different volume fractions at 20 °C versus shear rate. The basefluids with different volume fractions of Ethanol in DI (from 5 to 20%) are sheared from 17 S$^{-1}$ to 67 S$^{-1}$. As it can be seen in the Figure 4.35, viscosities of basefluids are independent of shear rate, indicating the Newtonian behavior of samples. The EtOH added to the Deionized Water, had no effect on the rheological behavior of basefluid in terms of shear thinning or thickening.

![Figure 4.35: Viscosity of different mixtures of DI+EtOH at T=20°C versus shear rate](image-url)
Figure 4.36 displays the effect of surfactant on basefluid viscosity for different volume percentages of ethanol. It is clear that the ethanol used in this case increases the viscosity of basefluid. In the Table 4.7, the increment of viscosity for different volume fraction of ethanol is calculated. Adding 5, 10, 15 and 20 % EtOH to the water rise 27, 47, 74, 94% viscosity of basefluid. It can be clearly concluded that raising the volume fraction of ethanol will increase the viscosity of basefluid.

![Figure 4.36: Viscosity of different mixtures of DI+EtOH at T=20°C](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Viscosity Average (Cp)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deionized Water</td>
<td>1.076</td>
<td>-</td>
</tr>
<tr>
<td>DI/EtOH (95/5 vol%)</td>
<td>1.37</td>
<td>27</td>
</tr>
<tr>
<td>DI/EtOH (90/10 vol%)</td>
<td>1.58</td>
<td>47</td>
</tr>
<tr>
<td>DI/EtOH (85/15 vol%)</td>
<td>1.87</td>
<td>74</td>
</tr>
<tr>
<td>DI/EtOH (80/20 vol%)</td>
<td>2.09</td>
<td>94</td>
</tr>
</tbody>
</table>

Figure 4.37 illustrates the viscosity of DI/EtOH based Al₂O₃ in different volume fractions at 20 °C as the function of shear rate. The 3 wt % nanofluid are prepared in different volume fractions of Ethanol in DI (from 5 to 20%) as basefluid and sheared from 17 S⁻¹ to 67 S⁻¹. Similarly, the viscosity of nanofluid is independent of shear rate which is representative for a Newtonian behavior of samples. The Al₂O₃ (3 wt%) added to the Deionized and EtOH had no effect on the rheological behavior of basefluid in terms of shear thinning or thickening.
Figure 4.37: Viscosity of different mixtures of DI+EtOH with Al₂O₃ (3 wt%) at T=20°C versus shear rate

Figure 4.38 exhibits the effect of ethanol on nanofluids viscosity for different volume percentages. It is clear that the ethanol used in this case, increases the viscosity of nanofluids as well. In the Table 4.8, increment percentage of viscosity for different volume fractions of ethanol is calculated. Adding 5, 10, 15 and 20 % EtOH to the water-based Al₂O₃ (3 wt%) bring about 17, 35, 58, 80 % viscosity increment of nanofluids. It can be concluded that raising the volume fraction of ethanol will increase the viscosity of nanofluid.

Figure 4.38: Viscosity of different mixtures of DI+EtOH with Al₂O₃ (3 wt%) nanoparticles inside at T=20°C
Table 4.8: Percentage of viscosity increment for different mixtures of DI+EtOH with Al₂O₃ (3 wt%) at T=20°C

<table>
<thead>
<tr>
<th>Material</th>
<th>Viscosity Average (Cp)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI/Al₂O₃ (3 wt%)</td>
<td>1.15</td>
<td>0</td>
</tr>
<tr>
<td>DI+EtOH (95/5 vol%)/Al₂O₃ (3 wt%)</td>
<td>1.34</td>
<td>17</td>
</tr>
<tr>
<td>DI+EtOH (90/10 vol%)/Al₂O₃ (3 wt%)</td>
<td>1.56</td>
<td>35</td>
</tr>
<tr>
<td>DI+EtOH (85/15 vol%)/Al₂O₃ (3 wt%)</td>
<td>1.82</td>
<td>58</td>
</tr>
<tr>
<td>DI+EtOH (80/20 vol%)/Al₂O₃ (3 wt%)</td>
<td>2.07</td>
<td>80</td>
</tr>
</tbody>
</table>

4.1.4.3.5. Effect of Sonication-Time on viscosity

Sonication time is another influential factor on viscosity of nanofluids. Since the interaction of nanoparticles inside the fluid is important for heat transfer phenomenon, it would be worth to see the effect on viscosity of nanofluids. Figure 4.39 illustrates the effect of sonication time on viscosity of two water-based Al₂O₃ (9 wt%). The size of particle is the only difference of these nanofluids (50 and 110 nm). Meanwhile, all nanofluids measured at T=20 °C showed Newtonian behavior.

As it can be seen in this figure, there is a decrement for viscosity of these two nanofluids by increasing the sonification. Al₂O₃ with 110 nm particle size has a marked decline in viscosity by sonication time. However, viscosity of the other nanofluid with smaller particle size changes smoothly by sonication time.

Table 4.9 indicates that the increment of viscosity for nanofluid with 50 nm particle size changes from 121 % to around 66%. For the nanofluid with 110 nm particle size, viscosity alters from 350% for nanofluid with no sonication time to 57% at 60 minutes sonication time (zero minute sonication time means measurement after shaking the sample by hand).

In other words, there is a possibility of turning down viscosity around 33% and 186% for water-based Al₂O₃ (9 wt%) with particle size of 50nm and 110 nm, respectively.

![Graph: Effect of Sonication time on Viscosity](image)

Figure 4.39: Viscosity of DW/Al₂O₃ (9 wt%) at different sonication time
Table 4.9: Viscosity increment of water adding EtOH surfactant at T=20 °C

<table>
<thead>
<tr>
<th>Material</th>
<th>Increment (%)</th>
<th>T$_{Soni} = 0$ min</th>
<th>Increment (%)</th>
<th>T$_{Soni} = 20$ min</th>
<th>Increment (%)</th>
<th>T$_{Soni} = 40$ min</th>
<th>Increment (%)</th>
<th>T$_{Soni} = 60$ min</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW/Al$_2$O$_3$ - 50 nm</td>
<td>121.16</td>
<td>76.60</td>
<td>67.26</td>
<td>65.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW/Al$_2$O$_3$ - 110 nm</td>
<td>349.43</td>
<td>178.86</td>
<td>112.29</td>
<td>56.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.40 depicts the effect of sonication time on viscosity of four different AFN/DW based Al$_2$O$_3$ (9 wt%) nanofluids. Nanofluids including particle size of 40, 150, 250 and 800 nm was measured within different sonication times. Similar conditions are considered for all nanofluids (as water-based Al$_2$O$_3$). They all measured at T=20 °C and showed Newtonian behavior.

As it can be perceived from the Figure 4.40, there is a completely different viscosity behavior of these bunches of nanofluids than two water nanofluids by increasing the sonification. Al$_2$O$_3$ with 40, 150 and 800 nm particle size have a decrement of viscosity increasing the sonication time up to 20 minutes. Afterwards, the viscosity of nanofluids rises by sonication time from 20 to 60 minutes. It means that there would be an optimum point for viscosity based on sonication time which can be taken into account for nanofluid applications. It should also be mentioned that since Al$_2$O$_3$ with 800 nm particle size showed a non-Newtonian behavior, the comparisons are done at shear rate of 71S$^{-1}$ in this case. On the other hand, Al$_2$O$_3$ with 250 nm particle size shows an increment regarding sonication time. The lowest viscosity is relating to zero minutes sonication time where measurement was performed after shaking the sample by hand. Moreover, as the former result showed, viscosity of the nanofluid with smaller particle size changes smoothly by sonication time.

Table 4.10 indicates that the increment of viscosity for nanofluid with 40, 150 and 800 nm particle size minimized at 20 minutes sonication time by around 54.5, 36, and 102%, respectively. For the nanofluid with 40, 150 nm particle size, viscosity changes after 60 minutes sonication time is the same as measurement with no sonication time.

Figure 4.40: Viscosity of DW+AFN/Al$_2$O$_3$ (9 wt%) at different sonication time
Table 4.10: Percentage of Viscosity increment of DW+AFN/Al₂O₃ (9 wt%) at different sonication time

<table>
<thead>
<tr>
<th>Material</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T_{soni} = 0 min</td>
<td>T_{soni} = 20 min</td>
<td>T_{soni} = 40 min</td>
<td>T_{soni} = 60 min</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃-40 nm</td>
<td>61.65</td>
<td>54.49</td>
<td>51.39</td>
<td>60.22</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃-150 nm</td>
<td>43.56</td>
<td>35.96</td>
<td>40.33</td>
<td>41.73</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃-250 nm</td>
<td>25.41</td>
<td>26.09</td>
<td>28.74</td>
<td>36.67</td>
</tr>
<tr>
<td>DW+AFN/Al₂O₃-800 nm</td>
<td>116.88</td>
<td>101.90</td>
<td>108.93</td>
<td>132.43</td>
</tr>
</tbody>
</table>

4.1.4.3.6. Effect of Temperature on Viscosity

Based on experimental data that are available in the literature, temperature is one of crucial factors which has a profound effect on rheological behavior of nanofluids. In order to investigate this parameter, two groups of nanofluid are selected (EG based CeO₂ and DEG based Cu). Viscosity of both groups showed no change by increasing the share rate and demonstrated their Newtonian behavior.

Figure 4.41 displays that increase in temperature decreases the viscosity of nanofluids. DEG based nanofluids (0.6 and 0.8 wt% Cu), which show almost similar viscosity in each temperature, change from about 40 cP at T= 20°C to 8.6 at T= 60 °C, indicating about 367% and 375% reduction in viscosity, respectively. The same story happens to EG based nanofluids (0.5 and 5 wt% CeO₂). The viscosity of 0.5 and 5 wt% CeO₂ reduce from 21 cP and 23 cP at T=20 °C to about 5.5 cP at T=60 °C. There is exactly same reduction in viscosity for both EG based nanofluid, around 284% viscosity reduction from T= 20°C to T= 60 °C. It can be interestingly concluded that using nanofluids (similar to convectional base fluids) in higher temperature would cost less for pumping power.

![Figure 4.41: Viscosity of different nanofluids versus temperature](image)

Table 4.11 indicates that the viscosity increment for both nanofluids (EG/CeO₂, DEG/Cu) at all temperatures is rather similar. For EG/CeO₂ (0.5 wt% and 5.0 wt% ) the average viscosity increment are
1.6% and 11%. The DEG based nanofluids, DEG/Cu (0.6 wt% and 0.8 wt%) also showed average difference of 9.8% and 10.8%, respectively.

### Table 4.11: Percentage of Viscosity increment of different nanofluids versus temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>Increment(%) T=20 °C</th>
<th>Increment(%) T=30 °C</th>
<th>Increment(%) T=40 °C</th>
<th>Increment(%) T=50 °C</th>
<th>Increment(%) T=60 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG/CeO$_2$ (0.5 wt%)</td>
<td>1.77</td>
<td>1.69</td>
<td>1.35</td>
<td>1.83</td>
<td>1.42</td>
</tr>
<tr>
<td>EG/CeO$_2$ (5.0 wt%)</td>
<td>11.81</td>
<td>10.51</td>
<td>10.69</td>
<td>10.65</td>
<td>11.49</td>
</tr>
<tr>
<td>DEG/Cu (0.6 wt%)</td>
<td>11.42</td>
<td>9.48</td>
<td>9.74</td>
<td>8.99</td>
<td>9.79</td>
</tr>
<tr>
<td>DEG/Cu (0.8 wt%)</td>
<td>13.09</td>
<td>12.58</td>
<td>10.14</td>
<td>8.97</td>
<td>9.57</td>
</tr>
</tbody>
</table>

Meanwhile, temperature like volume concentration and particle size may affect dependency of nanofluid viscosity on shear rate. In other words, temperature also can change the behavior of nanofluid from Newtonian to non-Newtonian. Figure 4.42 exhibits the change of viscosity versus temperature. As it is illustrated, the behavior of nanofluid in temperatures 20, 30 and 40 °C is Newtonian as same as its basefluid whereas rising the temperature shows dependency of nanofluid on shear rate.

From T= 50 °C, rheological behavior of CeO$_2$ illustrates a tendency to change from Newtonian to non-Newtonian. Rising the temperature, the tendency of showing non-Newtonian behavior shows itself more.
5. Stability of Nanofluids

Make a stable nanofluid is one tremendous concern within nanofluid preparation particularly if it is intended to be applicable in industry. Energy department of KTH in cooperation with department of Material Sciences has investigated stability measurement within their research activity. In this section, evaluation method and instrument will be described. Afterwards, results of some tests regarding stability of nanofluids will be depicted.

5.1. Evaluation method

As it was mentioned earlier, some methods are introduced to evaluate stability of nanofluids. Sedimentation balance method and Sedimentation photograph capturing are two methods, which might be considered as easier methods of evaluation.

In KTH laboratory, an instrument was manufactured to evaluate stability of nanofluids based on sedimentation balance method which can be seen in Figure 5.1. Experimental setup is included beaker (sample holder), round particles platform with hanging rod, frames for holding platform and beaker, adjustment screw, accurate balance and computer. Particle platform is in direct contact with high accurate scale (AX205 Delta Range) with readability of 0.01 mg and it is connected to the computer processor by the software of Mettler Toledo mtgx Balance. Adjustment screw is used to set height of beaker and whenever faster measurement is required, height can be decreased.

![Figure 5.1: First experimental setup for measuring stability (left), frame and sample holder on the balance (right)](image)

Initial test was performed using AFN/ CeO₂ as sample with particle concentration of 1 wt%. Test was done after 10-minute bath sonication of nanofluid and weight of settled particles was measured every 10 minutes for about 1 week. Figure 5.2 illustrates weight of particles in gram versus time.
However, there were some problems to measure stability with mentioned instrument, e.g. connecting rod of particle platform was not straight that might influence on its static equilibrium especially when platform accumulate nanoparticles during measurement. In addition, platform was required to be a bit smaller and deeper to provide results that are more accurate. Therefore, instrument was developed.
The second instrument shown in Figure 5.3 is comprising:

1.1. Vibration free table
1.2. High precision weighing balance
1.3. Coupled wire frame
1.4. Stand
1.5. Hanging wires and platform for accumulating nanoparticles
1.6. Sample holder
1.7. Transparent envelop
1.8. Temperature and humidity controllers (Not installed for following tests)
1.9. Computer processor

Apparatus is designed so that the static equilibrium of the hanging wire and platform would be expressed as one significant benefit of it compared to former device. Using the designed apparatus and method (Figure 5.4), a high accuracy measurement to evaluate the stability of nanofluids is achievable.

![Figure 5.4: Modified instrument to measure sedimentation rate of nanofluids](image)

### 5.2. Experimental result

Stability of different samples was tested by applying newly built instrument described earlier. List of the samples can be observed in Table 5.1.
Obtained result of the measurement has been categorized in four sections for samples number 1 to 4 as follow. It is worth mentioning that ambient temperature of the measurement time was 23°C for all cases.

5.2.1. Effect of particles concentration on stability

As it can be seen in Table 5.1, DW/china clay nanofluid is composed of three samples with different concentrations including 1.75 and 9% by weight of china clay nanoparticles. The test was accomplished for around 12000 minutes (More than 8 days) and result can be observed in Figure 5.5 in which CC is abbreviation of china clay while samples have been determined with Greek digits as type of 1, 2 and 3. Measurement data reveals that china clay with 1.75 wt% of nanoparticles (CC(I)) has much lower sedimentation in gram in comparison with other two types.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Basefluid</th>
<th>Basefluid concentration (Vol %)</th>
<th>Nanoparticle</th>
<th>Ambient Temperature (°C)</th>
<th>Particle Concentration (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DW</td>
<td>100</td>
<td>China Clay</td>
<td>23</td>
<td>1.75, 9, 9</td>
</tr>
<tr>
<td>2</td>
<td>DW</td>
<td>100</td>
<td>Al₂O₃</td>
<td>23</td>
<td>3, 6, 9</td>
</tr>
<tr>
<td>3</td>
<td>EG</td>
<td>100</td>
<td>CeO₂</td>
<td>23</td>
<td>1, 2</td>
</tr>
<tr>
<td>4</td>
<td>DW+EG</td>
<td>50/50</td>
<td>CeO₂</td>
<td>23</td>
<td>9</td>
</tr>
</tbody>
</table>

![Sedimentation of DW / china clay Nanofluids](image)

*Figure 5.5: Sedimentation of china clay type I, II and III*

For more detailed investigation, sedimentation of china clay samples during 120 minutes has been plotted in Figure 5.6. Due to different processes during preparation phase, CC II has lower weight of sedimentation from two other samples which means it is more stable nanofluid.
Sedimentation rate of nanoparticles in 12000 minutes has been depicted in Figure 5.7. More variation belongs to CC type 2 that shows it is more stable compared to two other types of china clay. In addition, this fact can be observed in Figure 5.8 in which sedimentation rate in 120 minutes has been displayed and once more it can be stated that CC II has more stability since its sedimentation rate over the time is lower than the others. It should be taken into account that slope of the curve is also low. For CC I sedimentation will be zero after about 70 minutes which means sample has settled completely.

In Figure 5.8, sedimentation rate of three china clay samples within first 120 minutes has been plotted. It
is obvious that china clay type II nanofluid shows different sedimentation behavior at the beginning compared to the other two and the rate of sedimentation is increasing. The behavior of fast sedimentation regarding china clay III at the beginning may refer to its lower viscosity and on the other hand material and shape of nanoparticles.

**Figure 5.8: Sedimentation rate of china clay type I, II and III**

Stability of water-based nanofluids, with Al$_2$O$_3$ as nanofluids in 3, 6 and 9 wt%, has been measured and result regarding sedimentation of nanoparticles is depicted in Figure 5.9. Test was run for about 3000 minutes for all samples. It can be seen that sample with 6 weight percentage of Al$_2$O$_3$ has higher value of sedimentation compared with two other types.

**Figure 5.9: Sedimentation of Al$_2$O$_3$ water-based nanofluids (3, 6, and 9wt%)**
Sedimentation rate of the samples over the time has been determined as well which can be viewed in figure below. Sample with 3 wt% has more fluctuations rather than two other samples.

![Figure 5.10: Sedimentation rate for Al₂O₃ water-based nanofluids (3, 6, and 9wt%)](image)

Ethylene glycol-based nanofluids were another set of samples which their stability has been investigated where CeO₂ nanoparticles (1 and 2% wt%) were dispersed inside EG. In this case, experiment time was about 3000 minutes which can be observed in Figure 5.11. Sedimentation of two samples by increasing time has been investigated. Regarding obtained values, sample with higher weight percentage of nanoparticles (CeO₂ 2wt%) contains higher sedimentation in gram which is expected.

![Figure 5.11: Sedimentation for CeO₂ (1 and 2 wt %) in ethylene glycol](image)
Moreover, Figure 5.12 shows sedimentation rate of EG/CeO$_2$ nanofluid in two different particle concentrations and it can be interpreted from the graph that sample with lower weight concentration is more stable and have longer time of stability.

![Sedimentation Rate of EG / CeO$_2$ Nanofluid](image)

*Figure 5.12: Sedimentation rate for CeO$_2$ (1 and 2 wt %) in ethylene glycol*

### 5.2.2. Effect of particles sonication on stability

Effect of sonication on sedimentation of nanofluid has been investigated. For this test, sedimentation of CeO$_2$ (9 wt%) in ethylene glycol has been tested before and after bath sonication. Experimental result indicates that sonication can prolong time of sedimentation as it can be seen in Figure 5.13.

![Sedimentation Versus Time Regarding Time Sonication](image)

*Figure 5.13: Sedimentation for CeO$_2$ in the mixture of ethylene glycol & DW (50 vol%) before and after sonication*
Sedimentation rate of the sample before and after sonication over the time have been shown in Figure 5.14. Based on results of this test, sample without bath sonication showed more fluctuations.

Figure 5.14: Sedimentation rate for CeO$_2$ in the mixture of ethylene glycol & DW (50% vol) before and after sonication
6. Integrated consideration of nanofluid properties

In this section, interaction among three properties, i.e. thermal conductivity, viscosity and stability tried to be considered. Thermal conductivity and viscosity relation has been studied by means of relative thermal conductivity to relative viscosity factor. Afterwards, effect of sedimentation on thermal conductivity and viscosity will be shown.

6.1. Thermal conductivity and viscosity

Many efforts allocated to improve heat transfer performance of nanofluids applied as a coolant. There is a real need to have a multi-lateral consideration about effect of adding nanoparticles to the basefluid. Although the aim of nanoparticle addition is raising the thermal properties, it is essential to see other effects of this addition on basefluid. Thus, other properties of nanofluids should be considered besides thermal properties, e.g. viscosity, stability, etc. This is a matter of cost to disperse nanoparticles in basefluids to increase the heat removal and dissipation capability of fluid. On the other hand, it is required to see viscosity, stability, wettability, etc economically. Therefore, in this thesis, relative thermal conductivity to relative viscosity has been investigated. The factor may evaluate thermal properties effectiveness versus power needed to shear the nanofluid (pumping power). Whereas, relative thermal conductivity and viscosity are defined as below:

\[ k_r = \frac{k_{nf}}{k_{bf}} \]  

\[ \mu_r = \frac{\mu_{nf}}{\mu_{bf}} \]  

Firstly, 3 samples, composed of distilled water and AFN (50% by volume) with Aluminum oxide nanoparticles (weight concentration of 9 percent), has been tested. Size of Al\(_2\)O\(_3\) particles were vary for each sample which can be seen in Figure 6.1.

![Figure 6.1: Relative thermal conductivity to relative viscosity of DW+AFN/Al\(_2\)O\(_3\) nanofluid at different temperatures](image)
Increase in temperature leads to increase of relative thermal conductivity to relative viscosity. In other words, thermal conductivity of nanofluid to basefluid increases with higher rate compared to viscosity of nanofluid to basefluid. It can be interpreted that this type of nanofluid is proper option to be applied in higher temperatures.

Furthermore, for all temperatures the factor is smaller than one which means relative thermal conductivity increment has smaller value than relative viscosity increment. It can be stated that higher value for the factor might be as an indicator to recognize applicability of nanofluid, i.e. higher value for the factor shows more applicable nanofluid with higher thermal conductivity and less viscosity.

Silver nanofluid with two different shapes has been investigated in this section. Figure 6.2 depicts these two nanofluids with ascending trend which means suitability of this nanofluid like previous one. Although, spherical shape nanofluid has lower increment of thermal conductivity compared to fiber-shaped one, it has higher value for relative thermal conductivity to relative viscosity. According to this factor, it would be said that the nanofluid containing spherical shaped nanoparticles has better overall performance, including viscosity and thermal conductivity.

Moreover, in order to investigate and recognize proper nanofluids economically, the cost functionality of each parameter such as viscosity and thermal conductivity should be defined. Then, it would be suggested a cost factor which can evaluate nanofluid applicability, i.e. 

\[ C_{r,\text{total}} = \frac{C_1(k_r) + C_2(\mu_r) + \ldots + C_l(x)}{\sum_{l=1}^{l}} \]

\( C_1(k_r) \) is representative of relative thermal cost for the system using nanofluid to the cost for the system using basefluid

\( C_2(\mu_r) \) is representative of relative pumping power cost for the system using nanofluid to the cost for the system using basefluid

\( C_l(x) \) is representative of relative specific feature (feature of x) cost for the system using nanofluid to the cost for the system using basefluid

- \( C_{r,\text{total}} < 1 \) if Cost effective nanofluid,
- \( C_{r,\text{total}} > 1 \) if It does not cost effective nanofluid,
- \( C_{r,\text{total}} = 1 \) if No difference between applying nanofluid and basefluid.
Finally, AFN/CeO$_2$ nanofluids with two different weight concentrations have been tested. Descending trend of them by changing temperature can be seen in Figure 6.3. Trend shows that applicability of this type of nanofluid as coolant or working fluid would not be confirmed in high temperatures. However, since it was mentioned earlier, this kind of investigation is only matter of cost and there is a need to define cost functionality of each factor to give a definite judge about applicability of nanofluids.
6.2. Stability, thermal conductivity and viscosity

Effect of sedimentation on thermal conductivity and viscosity will be discussed in this part.

6.2.1. Sedimentation and thermal conductivity

To observe the influence of particle sedimentation on thermal conductivity and viscosity, two tests were performed. In the first test, EG+DW (50% by volume) with silver (2 wt%) nanofluid was shaken and injected into sample holder. Initially, temperature of thermal bath was set to 20 °C and thermal conductivity measurement of nanofluid was done while temperature was increasing up to 50 °C. Trend of thermal conductivity has been depicted in Figure 6.4 with green triangles. Afterward, nanofluid was shaken once more to do the test reversely, i.e. thermal conductivity was measuring at 50°C up to 20°C with 10 °C temperature interval. The trend of the thermal conductivity for the second test is also obvious in Figure 6.4.

Based on these experiments, it can be perceived that thermal conductivity of nanofluid from 50°C to 20°C has lower values at 20 °C and 30 °C contrasted to changing the temperature from 20°C to 50°C. It might be regarded as the effect of sedimentation on thermal conductivity. Higher temperature causes lower viscosity and based on Stokes’ Law, it results in faster sedimentation of nanoparticles inside the fluid. Thus, when we start the test at 50 °C, faster sedimentation of nanoparticles causes slipper slop of the thermal conductivity curve compared to starting at temperature of 20 °C. It also should be noted that at T=50 °C second test showed higher value for thermal conductivity since it is due to as lower rate of sedimentation. Table 6.1 shows the exact percentage of increment for each test.

![Figure 6.4: Thermal conductivity of EG+DW / Ag (2 wt%) Nanofluid](image)
Table 6.1: Thermal conductivity enhancement of EG+DW / Ag (2 wt%) nanofluid

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>From 50 °C to 20 °C</th>
<th>From 20 °C to 50 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>11.36</td>
<td>18.49</td>
</tr>
<tr>
<td>30</td>
<td>12.10</td>
<td>17.55</td>
</tr>
<tr>
<td>40</td>
<td>14.35</td>
<td>14.25</td>
</tr>
<tr>
<td>50</td>
<td>16.66</td>
<td>15.41</td>
</tr>
</tbody>
</table>

6.2.2. Sedimentation and viscosity

Effect of sedimentation on viscosity of nanofluid over the time was tested as well. Sample was a nanofluid composing DW and AFN (50% by volume) as basefluid and CeO₂ (9 wt%) as nanoparticle. It can be observed in Figure 6.5 that viscosity is decreasing over the time. The reason would be sedimentation of nanoparticles during the time.

Figure 6.5: Viscosity of DW+AFN/CeO₂ (9 wt%) over 200 minutes
7. Conclusion and Outlook

In the present study, the evaluation of nanofluids based on different properties is done. The investigation was about considering several effective parameters on thermal and rheological properties of nanofluids. The effective parameters discovered through the literature review, which were introduced by former researches, and using different measurement setups, effectiveness of those factors have disclosed by experimental tests. The thermal transport properties of nanofluids including thermal conductivity, viscosity and stability were measured.

Regarding thermal conductivity of nanofluids, which was measured by Transient Plane Source (TPS) method, parameters such as temperature, morphology, concentration, sonication time and alcohol addition were taken into account to indicate factors leading increment/decrement of nanofluids’ thermal conductivity. Based on measurements, increasing temperature, concentration and sonication time lead to increase in thermal conductivity of nanofluids while growing nanoparticle size (up to specific size) and adding ethanol result in lessening thermal conductivity.

Shape of nanoparticles also showed considerable effect on thermal conductivity. Thermal conductivity of nanofluid containing fiber-shaped nanoparticles was higher than one with spherical particles. Meanwhile, the preparation methods were considered and it was found that it has a significant influence on thermal conductivity. In general, adding solid nanoparticles increases thermal conductivity of nanofluid but not as much as what was reported in some literatures. SiC and silver (2 wt%) nanofluids showed higher enhancement in thermal conductivity among several examined samples. Increase in thermal conductivity of nanofluid compared to basefluid was about 18% for SiC nanofluid and from 14% to 18% for silver nanofluid with fiber-shaped nanoparticles.

Similar investigation was performed for viscosity. Effective parameters on viscosity were considered which was temperature, morphology, shape, size of nanoparticle, sonication time, alcohol, dispersion method and shear rate. The viscosity measurements done by rotating coaxial cylinder viscometer (Brookfield DV-II+Pro Viscometer) showed that increase in concentration of nanoparticles and adding ethanol will contribute to enhancement of the viscosity while it reduces by ascending temperature, nanoparticle size (up to specific size), sonication time and shear rate for non-Newtonian nanofluids (Shear thinning/pseudo plastic). The viscosity rose by increasing the particle size from 250 nm to 800 nm and increasing sonication time more than 20 minutes resulted in viscosity augmentation.

It should be noted that the particle size and sonication time might have optimum point regarding the measurements for thermal conductivity and viscosity of nanofluids.

Stability of nanofluids was also investigated using sedimentation balance method and some effective parameters like sonication and volume concentration were studied. Tests showed that increase in volume concentration led to higher rate of sedimentation. It was also proved that the sonication of nanofluid would improve the stability of nanoparticles inside the nanofluid.

Eventually, study the effect of sedimentation on two other properties revealed that sedimentation of nanoparticles leads to reduction of thermal conductivity and viscosity. In addition, relative thermal conductivity to relative viscosity factor can be used to evaluate probable applicability of nanofluids to some extent. Indeed, for this factor, as high as possible value is desired and ascending trend of graph shows better performance of nanofluid in high temperatures while descending trend of it shows better performance in low temperatures.
For further research activities, the following suggestions should be considered:

- Thermal bath of TPS analyzer should be calibrated.
- Sample holder of viscometer should be insulated to avoid ambient effect.
- Sample holder of TPS analyzer should be modified to have faster and more accurate measurement values.
- $k/\mu$ factor might be considered for evaluation of nanofluids. Based on that, a mathematical model can be developed as well.
- It would be suggested to focus more on microscopic investigation regarding behavior of nanofluids besides macroscopic study including physics of nanofluids, molecular interaction, heat transfer mechanisms and so forth.
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Appendices

A. Bath Performance of TPS Analyzer

A.1. Dry Shell

Monitoring temperature of bath, clamp and shell has been performed from 40 °C to 50 °C for dry shell. It can be seen in the figure that after more than 1500 seconds, temperature of the sample cannot meet bath temperature due to air gap between sample holder and shell.

![Dry shell-From 30°C to 40°C](image1)

*Figure A.1: Temperature monitoring of bath and sample holder over the time from T=30°C to T=40°C for dry shell*

![Dry Shell-Set Point=40°C](image2)

*Figure A.2: Temperature monitoring of bath and sample holder over the time at T=40°C for dry shell*
Average values for clamp, shell and bath in comparison with adjusted temperature has been shown in figure below.

![Average Value/Dry Shell, Set Point=40°C](image)

**Figure A.3:** Average temperature of clamp, shell and bath compared to adjusted temperature at $T=40^\circ C$ for dry shell

Altering from 40 °C to 50 °C for dry shell results in following graph showing temperature versus time.

![Dry shell-From 40°C to 50°C](image)

**Figure A.4:** Temperature monitoring of bath and sample holder over the time from $T=40^\circ C$ to $T=50^\circ C$ for dry shell
Finally, set point is 50°C and sample temperature cannot meet set bath temperature.

![Figure A.5: Temperature monitoring of bath and sample holder over the time at T=50°C for dry shell](image)

Average values of temperature for different sections have been depicted below.

![Figure A.6: Average temperature of clamp, shell and bath compared to adjusted temperature at T=50°C for dry shell](image)
A.2. Wet shell

Same experiments as dry shell, has been performed for wet shell which showed much better results. Within altering temperature form 30 °C to 40 °C, after about 700 seconds equilibrium in temperature occurs.

Figure A.7: Temperature monitoring of bath and sample holder over the time from T=30°C to T=40°C for wet shell

Figure A.8: Temperature monitoring of bath and sample holder over the time at T=40°C for wet shell
For wet shell, 700 seconds should be suitable waiting time for reaching from 40 °C to 50 °C that it can be seen in figure below.

\[\text{Figure A.9: Average temperature of clamp, shell and bath compared to adjusted temperature at } T=40^\circ\text{C for wet shell}\]

\[\text{Figure A.10: Temperature monitoring of bath and sample holder over the time from } T=40^\circ\text{C to } T=50^\circ\text{C for wet shell}\]
Figure A.11: Temperature monitoring of bath and sample holder over the time at \( T=50^\circ C \) for wet shell

Figure A.12: Average temperature of clamp, shell and bath compared to adjusted temperature at \( T=50^\circ C \) for wet shell
B. Bath Performance of Viscometer

Figure B.1: Bath performance for viscometer from temperature of 30 °C to 40 °C

Figure B.2: Temperature of each section at set point of $T=40$ °C
Figure B.3: Bath performance average temperature at T=40 °C

Figure B.4: Bath performance for viscometer from temperature of 40 °C to 50 °C
Figure B.5: Bath performance at $T=50^\circ C$

Figure B.6: Temperature of each section at set point of at $T=50^\circ C$
Figure B.7: Bath performance average temperature at T=50 °C

Figure B.8: Bath performance for viscometer from temperature of 50 °C to 60 °C
Figure B.9: Bath performance at $T=60\,^\circ C$

Figure B.10: Temperature of each section at set point of at $T=60\,^\circ C$
Figure B.11: Bath performance. average temperature at $T=60\,^\circ C$