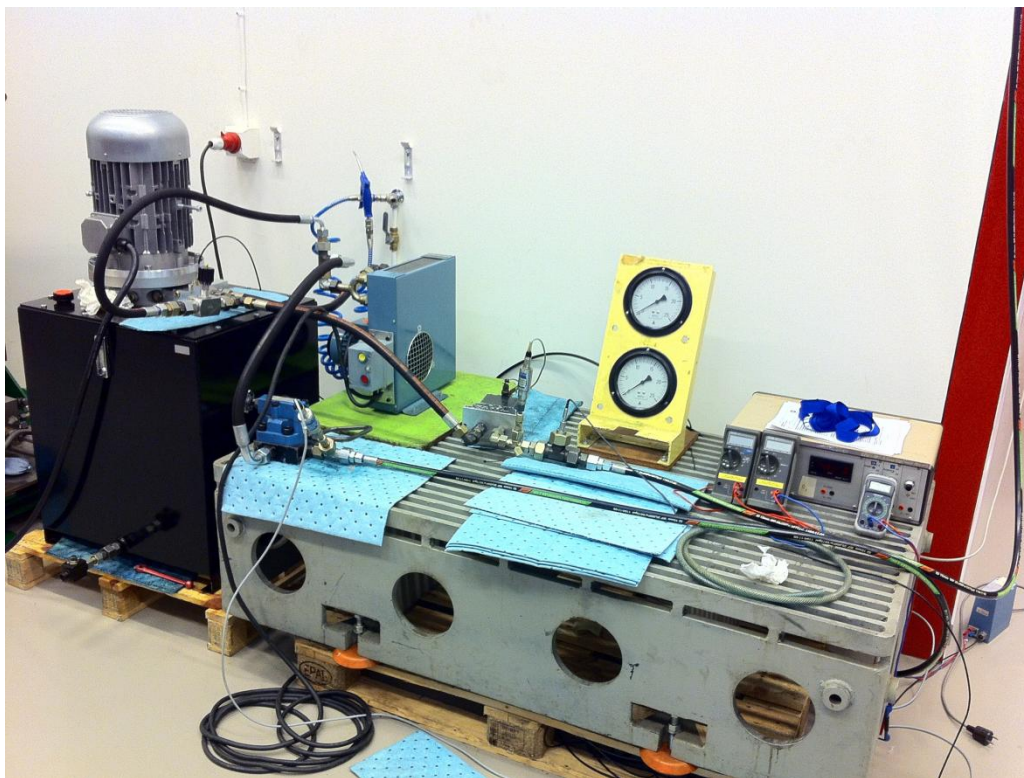




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Hydraulic fluid properties and its influence on system performance.

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Abstract:

Hence hydraulic fluid is the medium of power transfer in hydraulic equipment, it is important to know the properties of hydraulic fluids and its influence on system performance. There are different types of fluids based on their availability, working purpose etc. So selection of fluid depends on the working conditions of the hydraulic equipment. So to select a fluid one has to be clear about the operating conditions of hydraulic equipment and this can be achieved by testing the equipment with different fluids and select the fluid that gives the best performance. To know about the properties (like Viscosity, operating temperature range) of fluids available there should be some standardisation of hydraulic fluids and one such type is ISO (International organization for standardization). Though there are many this is followed by most. By this standardization the fluid manufacturer can categorize the fluids and the user can easily select the fluid according to their requirement.

The thesis work mainly deals with two parts. First part is giving a brief description of fluids based on ISO standards and standard test methods for hydraulic systems. The major or second part deals with finding the performance of six different types of fluids from four different manufacturers. Among them five fluids are environmentally acceptable hydraulic fluids and one is mineral oil based hydraulic fluid. The main task is to find the performance of this five environmentally acceptable hydraulic fluids comparing with standard mineral oil so that it will be useful for the equipment manufacturers to select a fluid for the system. The other main task of the thesis is to measure the pressure losses in long hoses which are used in forest machines. So a test plan was made to cover both the tasks, where the test method to find the losses in hose is one of the test method in finding the performances of the six fluids. The procedure about the tests are clearly explained in section 5.1. Among the five environmentally acceptable hydraulic fluids one is synthetic bio diesel and remaining four are synthetic ester based fluids and standard mineral oil is paraffin based. Because of the confidentiality the fluid names has been changed based on their viscosity as *diesel oil* (synthetic bio diesel), *synth 32*, *synth e 32*, *synth es 32*, *synth 12* and *mineral oil 46* (standard mineral oil). *Synth e 32* and *synth es 32* are the upgraded fluids of *synth 32* fluid from same manufacturer.

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1. Introduction

1.1. Background

The demand for the eco friendly synthetic hydraulic fluids is increasing day by day because of the depletion of the crude oil and to keep the environment safe. Though the fluid is eco friendly the hydraulic system performance should not be decreased. To find the system performance the fluid has to undergo many tests. These are the newly developed fluids and no hydraulic tests have been carried out. So one should be clear that what types of tests should be done and how the system should be built to test the fluid. The present test bench that is used is not a prearranged system. So it has to be assembled according to our requirement.

1.2. Objective

The main objectives of the thesis is to

1. To give a brief description of fluids and standard test methods.
2. Measure the viscosities of the fluids according to ISO 3104 standard.
3. Setting up of test bench for experiments.
4. Testing the system with different fluids and study the performance.
5. Simulating the system by using experimental data of test bench and compare this simulation results with test bench results.

1.3. Limitations of the system

Our aim is to change the flow and measure pressure drop across hose. This can be done in two ways, either by changing the speed of electric motor or by changing the displacement setting of the pump but both of them is not possible in our system because to change the speed of electric motor it needs a complicated electronics which would be expensive and it is also not possible to use the variable displacement pump because that it should be fixed inside the tank which is complicated to fix the controller to the pump to vary displacement setting.

So an alternate arrangement was made by letting out extra flow through an variable orifice which is explained clearly in section 4.1.

1.4. Hydraulic hose

The hose is long cylindrical tube designed to carry power in the form of fluids from one place to other. Hoses are generally made up of polyethylene, PVC, or synthetic or natural rubber with a combination of metal wires to give strength. Common parameters are diameter, wall thickness and pressure rating.



Fig. 1.1. Hydraulic hose

Pressure drops in the hose according to the formula

$$\Delta p_f = \lambda \frac{l}{d} \frac{\rho \cdot v^2}{2} \quad \text{for a straight hose}^{[1]}$$

Where λ is friction factor

$$\lambda = \frac{64}{Re} \quad \text{for } Re < 2300 \text{ (laminar flow)}$$

$$\lambda = \frac{0.316}{\sqrt[4]{Re}} \quad \text{for } 2300 < Re < 10^5 \text{ (Turbulent flow)}$$

l = length of the hose [m]

ρ = density of the fluid [kg/m³]

v = mean flow velocity [m/s],

d = diameter of the hose[m]

This is the pressure loss in hose when it is in straight line. The pressure loss increases with the angle of bend in the hose where the formula is not mentioned here. The calculation of Reynolds number is explained in section 4.2.6.

1.5. Volumetric efficiency model for pump

The flow losses in pump depends on the factors like pressure difference, viscosity of the fluid etc. which is based on the formula

$$\eta_{volp} = 1 - c_v \frac{\Delta p}{|\varepsilon_p| n_p \mu} \quad [1]$$

Where η_{volp} = volumetric efficiency of the pump

c_v = laminar leakage losses [-]

Δp = Pressure difference [Pa]

ε_p = displacement setting of the pump [-]

μ = dynamic viscosity [Ns/m²]

1.6. Synthetic esters

Synthetic oils are the artificially made chemical compounds instead of crude oil and esters are formed by reacting oxoacid with hydroxyl like the alcohol. Esters are derived from inorganic or organic acids. These are used in extreme temperatures because it has superior mechanical and chemical properties compared to mineral oil.

1.7. Ubbelohde viscometer

To find the viscosity index and to plot the viscosity temperature chart it is important to know the kinematic viscosities of the fluid at two different temperatures 40°C and 100°C. So to measure this ‘Ubbelohde viscometer’ has been used. Ubbelohde viscometer is a U shaped capillary type viscometer as in **fig. 1.2** to measure viscosity. It consists of reservoir at one end and measuring bulb with a capillary on the other end. The fluid is sucked from the reservoir through the capillary. The fluid is allowed back through the measuring bulb where the time

taken in seconds by the fluid to pass from one point to other in measuring bulb is multiplied with viscometer constant to find the kinematic viscosity [cSt] of the fluid. Unlike other viscometers the Ubbelohde viscometer has third arm starting from the capillary. By this the pressure head depends only on fixed height and not on total volume.^[2]

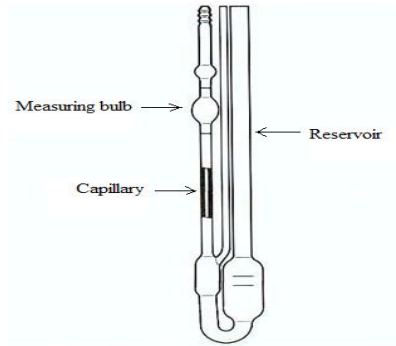


Fig.1.2. Ubbelohde viscometer

1.8. Viscosity temperature chart

The viscosity temperature chart is very useful to find the kinematic viscosity of the fluid at any temperature. Based on the ASTM D341 standard **viscosity-temperature chart** of all the fluids is plotted by using matlab program. To plot this kinematic viscosity of the fluid at 40°C and 100°C is necessary. For some of the fluids kinematic viscosities at 100°C are not given by manufacturers, so the kinematic viscosity at given 40°C and measured 100°C has been used to plot.

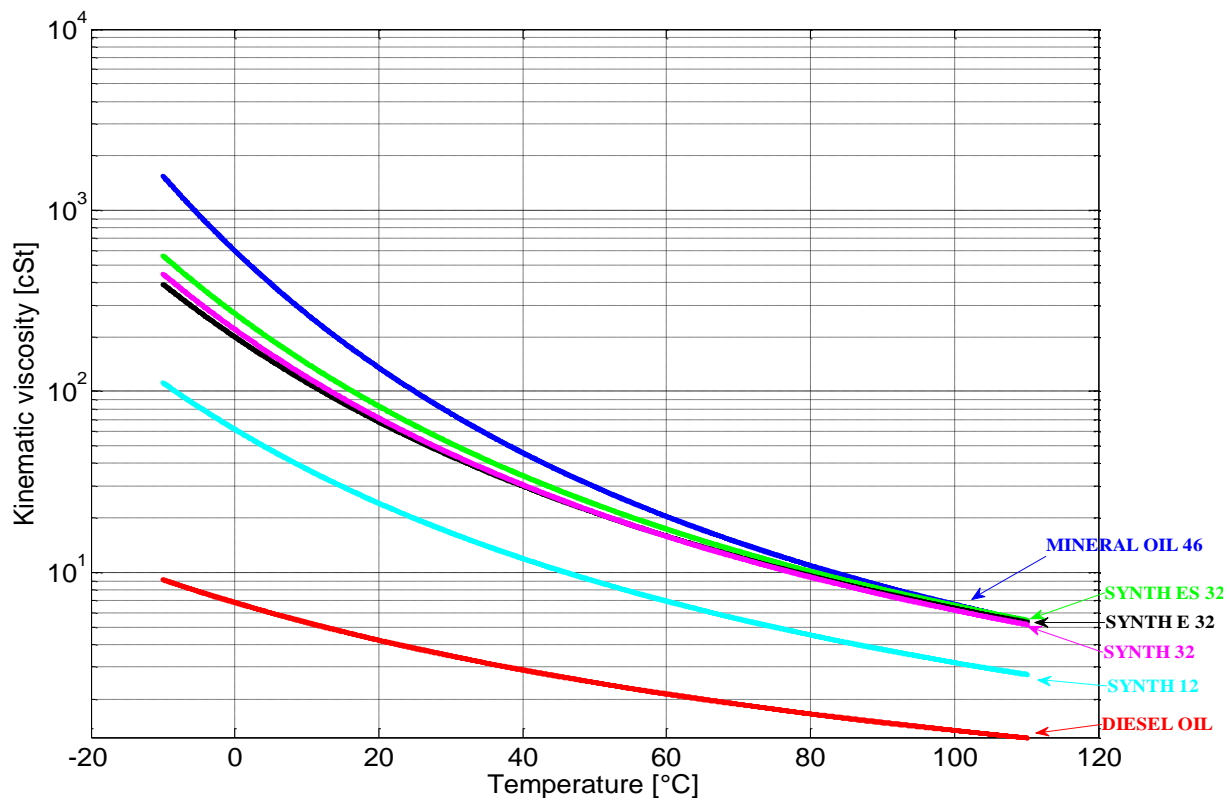


Fig.1.3 Viscosity temperature chart of all the fluids

1.9. Hydraulic fluids specifications

Some of the specifications of the fluids are not given mainly the kinematic viscosities of the fluids at 40°C and 100°C which are used to calculate viscosity index of the fluid. The kinematic viscosities of the fluids at both temperatures has been measured in flumes lab by using *Ubbelohde viscometer* where it is used in most of the test methods like ISO 3104, ISO 3105, ASTM D 445, ASTM D 446, BS 188, IP 71.

To calculate viscosity index of the petroleum products, lubricants or other types of hydraulic fluid according to 'ISO 2909:2002' or 'ASTM D2270 - 10e1' standards it requires kinematic viscosities [cSt] at two different temperature. One is at 40°C and other is at 100°C. But these two standards are used to calculate the viscosity index of the fluids from 2 cSt to 70 cSt at 100°C. The viscosity index of the fluids has calculated by using online calculator ^[3]. The difference in viscosities between the given data and the measured is due to error in the viscometer. But this does not affect in estimating the viscosity of the fluid with respect to temperature.

TYPE OF FLUID PROPERTY	DIESEL OIL	SYNTH 12	SYNTH 32	SYNTH E 32	SYNTH ES 32	MINERAL OIL 46
KINEMATIC VISCOSITY(Given)						
@40 ⁰ C [cSt]	2.6 to 4	12	30.6	30.1	34.4	46
@100 ⁰ C [cSt]		3.2	5.89			6.7
VISCOSITY INDEX (Given)		139	140			98
KINEMATIC VISCOSITY(Measured)						
@40 ⁰ C [cSt]	2.91311	11.86883	29.3887	29.4943	29.6339	41.2395
@100 ⁰ C [cSt]	1.34966	3.314926	6.2228	6.3877	6.6143	7.2763
VISCOSITY INDEX (Measured)		161	169	177	189	141.18
VISCOSITY INDEX (@Given 40⁰C and measured 100⁰C)		156	158	172	151	119.63
DENSITY @ 15⁰C [kg/m³]	800	947	920	936	896	879
FLASH POINT in [°C]	90	169	240	229	240	230
POUR POINT [°C]		-66	-58	-50		-30

Table. 1.1. Physical parameters of the fluids.

2. Hydraulic fluids

Hydraulic fluid is a medium to transfer power in the system or the machinery. Hydraulic fluids play a very important role in the developing world. The fluids are classified on the basis of their viscosity, which makes a chart which is useful for the industries to select the fluid for the particular function. The classifications ranges from a simple ISO (International Organization for Standardization) to the recent classification ASTM D 6080-97 (classifying based on viscosity).

2.1. Classification of hydraulic fluids based on ISO viscosity grade

Most of the fluids used are classified with ISO standards. The ISO standard fluids are mainly classified based on the kinematic viscosity at 40⁰C. The fluid is mainly taken at 40⁰C which is taken as a reference temperature between the maximum operating and the ambient temperatures. The ISO classification is done on 18 main fluids based on their viscosity grade. **Table.2.1** shows the viscosity range of a fluid on its ISO VG.

ISO Viscosity Grades based on kinematic Viscosity [centistokes/cSt] at 40 ⁰ C		
ISO VG	Minimum [cSt]	Maximum[cSt]
2	1.98	2.42
3	2.88	3.52
5	4.14	5.06
7	6.12	7.48
10	9.0	11
15	13.5	16.5
22	19.8	24.2
32	28.8	35.2
46	41.4	50.6
68	61.2	74.8
100	90	110
150	135	165
220	198	242

320	288	353
460	414	506
680	612	748
1000	900	1100
1500	1350	1650

Table.2.1. Classification of hydraulic fluids based on ISO Viscosity grade

2.2. Types of hydraulic fluids

According to ISO there are three different types of fluids according to their source of availability and purpose of use.^[4]

2.2.1. Mineral-Oil based Hydraulic fluids

As these have a mineral oil base, so they are named as Mineral-oil-Based Hydraulic fluids. This kind of fluids will have high performance at lower cost. These mineral oils are further classified as HH, HL and HM fluids.

Type HH fluids are refined mineral oil fluids which do not have any additives. These fluids are able to transfer power but have less properties of lubrication and unable to withstand high temperature. These types of fluid have a limited usage in industries. Some of the uses are manually used jacks and pumps, low pressure hydraulic system etc.

Type HL fluids are refined mineral oils which contain oxidants and rust inhibitors which help the system to be protected from chemical attack and water contamination. These fluids are mainly used in piston pump applications.

HM is a version of HL-type fluids which have improved anti-wear additives. These fluids use phosphorus, zinc and sulphur components to get their anti-wear properties. These are the fluids mainly used in the high pressure hydraulic system.

2.2.2. Fire Resistant Fluids

These fluids generate less heat when burnt than those of mineral oil based fluids. As the name suggests these fluids are mainly used in industries where there are chances of fire hazards, such as foundries, military, die-casting and basic metal industry. These fluids are made of lower BTU (British Thermal Unit) compared to those of mineral oil based fluids, such as water-glycol, phosphate ester and polyol esters. ISO have classified these fluids as HFAE(soluble oils), HFAS(high water-based fluids), HFB(invert emulsions), HFC(water glycols), HFDR(phosphate ester) and HRDU(polyol esters).

2.2.3. Environmental Acceptable Hydraulic Fluids (EAHF)

These fluids are basically used in the application where there is a risk of leakage or spills into the environment, which may cause some damage to the environment. These fluids are not harmful to the aquatic creatures and they are biodegradable. These fluids are used in forestry, lawn equipment, off-shore drilling, dams and maritime industries. The ISO have classified these fluids as HETG (based on natural vegetable oils), HEES (based on synthetic esters), HEPG (polyglycol fluids) and HEPR (polyalphaolefin types).

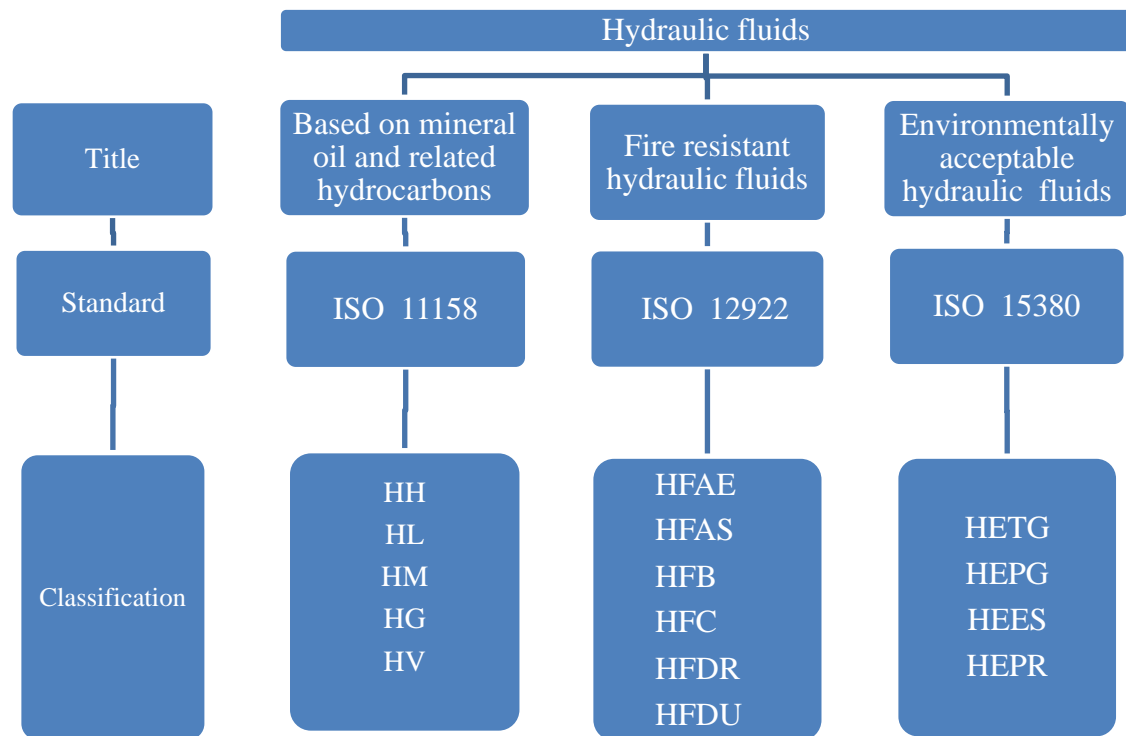


Chart.2.1. Classification of hydraulic fluids.^[5]

2.3. Fluid properties and comparative performances

While selecting a hydraulic fluid one has to be aware of hydraulic fluid properties and its effect on hydraulic system. Generally the hydraulic fluids have many properties and some of the important properties are explained in detail below.

2.3.1. Density (ρ)

Density is expressed as mass occupied in a unit volume. The density is inversely proportional to temperature.

The SI unit of density is kg/m^3

2.3.2. Viscosity ^[6]

The most important property of the hydraulic fluid to be considered is viscosity of the fluid. The main selection of fluid for the system depends on the viscosity of fluid. Viscosity is the measure of resistance of fluid flow that is inverse measure of fluidity. For example honey is very thick that means it is more viscous than water. Viscosity is directly related to system (especially pump and motor) wear, leakage, and most important efficiency.

2.3.2.1. Units of viscosity

1. Dynamic viscosity or absolute viscosity (μ)

Viscosity measured under force induced flow that is force per unit area (shear stress) required to move one surface over another in a second is called dynamic viscosity.

The SI unit of dynamic viscosity is *pascal second*($Pa \cdot s$) where $Pa = N/m^2$

The cgs unit of dynamic viscosity is *poise*(P)= $0.1 \text{ pascal second } (Pa \cdot s)$

The common usage and ASTM standard of dynamic viscosity is *centipoises* (cP)

$$\text{centipoise}(cP) = 10^{-2} \text{ poise}(P) = 10^{-3} \text{ Ns/m}^2$$

2. Kinematic viscosity (ν)

Generally kinematic viscosity is used for measurements. Viscosity measured under gravity induced is called kinematic viscosity. It is the ratio of dynamic viscosity and density.

$$\nu = \mu / \rho$$

The SI unit of μ is Ns/m^2 and ρ is kg/m^3

$$\text{Therefore the SI unit of } \nu \text{ is } \frac{\text{Ns/m}^2}{\text{kg/m}^3} = \frac{\text{kg/ms}}{\text{kg/m}^3} = \text{m}^2/\text{s}$$

The cgs unit of ν is *stokes*(St) = $\text{cm}^2/\text{s} = 10^{-4} \text{ m}^2/\text{s}$

But the general usage of ν is *centistokes* (cSt) = $\text{mm}^2/\text{s} = 10^{-6} \text{ m}^2/\text{s}$

2.3.3. Viscosity index (VI)

It indicates the temperature range within which the fluid can be used. It is a unitless value. The higher the VI, the better the stability of viscosity of fluid. If the VI of the fluid is low, the viscosity of fluid becomes very high at low temperatures and vice versa. The standard method to calculate viscosity index of petroleum products is ASTM D2270 or ISO 2909:2002. There are some limitations in this method as it is used to calculate the viscosity index of the fluids where the kinematic viscosity is above 2 cSt at 100°C.^[7]

2.3.4. Bulk modulus (β)

It is defined as the substance resistance to uniform compression, which is simply defined as change in volume by change in pressure. The hydraulic fluids require low compressibility that means high bulk modulus which is useful for high pressure transmission and low power losses. The fluid with low bulk modulus acts as damping material for hydraulic system, but for poor bulk modulus the line sizes should be increased to compensate for the lower stiffness.^[8]

The SI unit of bulk modulus is *Pascal* (Pa) = N/m^2

Fluid type		Typical operating temperature range. (As per ISO)	Bulk modulus (N/m ²)	Kinematic viscosity at 40°C according to ISO (cSt)
Mineral oil based	Mineral oil(paraffin)	37 to 70° C	1-1.66 ·10 ⁹	9 - 165
Fire resistant fluids	HFAE(Oil in water emulsions)	5 to 50° C	2.5·10 ⁹	6 - 60
	HFAS(Synthetic aqueous fluids)	5 to 50° C	2.5·10 ⁹	6 - 60
	HFB(water in oil / invert emulsions)	5 to 50° C	2.5·10 ⁹	41.4-110
	HFC(water polymer solutions/water glycols)	-20 to 50° C	3.5·10 ⁹	19.8-74.8
	HFDR(phosphate esters)	-20 to 150° C	2.3-2.8·10 ⁹	13.5-110
	HFDU(polyol esters)	-20 to 150° C	2.3-2.8·10 ⁹	13.5-110
Environ-mentally acceptable hydraulic fluids	HETG(natural vegetable oils)	-30 to 75° C	1.85·10 ⁹	19.8-74.8
	HEES(synthetic esters)	-25 to 115° C	2.3-2.8·10 ⁹	19.8-110
	HEPG(polyglycol)	-30 to 90° C	2.3-2.8·10 ⁹	19.8-74.8
	HEPR(polyalphaol efin)	-25 to 115° C	1.68·10 ⁹	19.8-74.8

Table.2.2. Physical parameters of kinematic viscosity, bulk modulus and operating temperatures.^{[9][10][11][12][13][14][15][16][17]}

2.3.5. Lubrication properties

Fluid type		Natural lubrication	Anti wear
Mineral oil based	Mineral oil(paraffin)	Good	Excellent
Fire resistant fluids	HFAE(Oil in water emulsions)	Fair	Fair
	HFAS(Synthetic aqueous fluids)	Good	Good
	HFB(water in oil / invert emulsions)	Good	Good
	HFC(water polymer solutions/water glycols)	Good	Good
	HFDR(phosphate esters)	Fair	Good
	HFDU(polyol esters)	Good	Very good
Environ-mentally acceptable hydraulic fluids	HETG(natural vegetable oils)	Excellent	Excellent
	HEES(synthetic esters)	Good	Very good
	HEPG(polyglycols)	Good	Very good
	HEPR(polyalphaolefin)	Good	Excellent

Table.2.3. Comparative performances based on natural lubrication and anti wear.^[17]

The hydraulic fluids should carry away the heat and it should protect the system from wear. The fluid with high VI shows better lubrication properties. During high working temperatures, if VI is low, the fluid becomes thin and wear occurs especially in pumps and motors. By adding VI improves the anti-wear properties of the fluid can be improved. Generally the vegetable oil have good lubrication properties compared to basic mineral oil. The **table** shows the natural lubrication anti-wear performance of different types of hydraulic fluids.

2.3.6. Environmental adaptability

Now-a-days the usage of environmentally acceptable hydraulic fluids is increasing, especially in European countries. These countries are using bio lubricants since 25 years. According to recent survey the total market share of bio lubricant is 3.2 % in Europe and growth was estimated to be 3.7 % from 2000 to 2006. Germany is using 15 % of bio lubricants and Scandinavia is not far behind which constitute for 11 %. Not all the bio lubricants are vegetable oil but they are synthetic too.^[18]

Three main criteria are considered while selecting the effect of hydraulic fluids on environment.

- Toxicity

- Biodegradability
- Bioaccumulation

2.3.6.1. Toxicity

It is very important to be considered for environment and safety of the people while selecting the hydraulic fluids. Although many precautions are taken it is important to be considered during spills and leakages. When there is a compulsory use of toxic fluid, safety measures are must. The different countries have their own standards for labelling bio lubricant. Some are

- Swedish Standard SS 15 54 34
- ASTM standards in USA

2.3.6.2. Biodegradability

The importance of biodegradability is increasing day by day globally, mainly in the areas of offshore drilling, harbour maintenance, forest machinery and snow removal. The trend for the use of biodegradable fluids started from Europe. There are two types of biodegradation tests primary and ultimate.

- Primary: It is the minimum change in the identity of substance.
- Ultimate: It is complete conversion of substance into carbon dioxide, water, inorganic salts and biomass.

The below table shows the biodegradation test conducted on hydraulic fluids in Europe.

Method		Criteria
Primary	CEC-L-33-A-93 21 day test Loss of hydrocarbon bond	> 67% (COMIA) > 80% (German blue angel)
Ultimate	Modified sturm (OECD 301B) 28 day test Carbon dioxide production Modified AFNOR(OECD 301A) 28 day test Loss of dissolved organic carbon	> 60% > 70%

Table.2.4. Biodegradability tests ^{[17] [19]}

2.3.7. Stability of hydraulic fluids

The stability of the hydraulic fluid is also an important factor while selecting the fluid because of its operating conditions. Below table shows the comparative performances of hydrolytic, thermal and oxidation stabilities of different types of hydraulic fluids.

Fluid type		Thermal	Oxidation	Hydrolytic
Mineral oil based	Mineral oil(paraffin)	Good	Fair	Excellent
Fire resistant fluids	HFAE(Oil in water emulsions)	Good	Very good	Good
	HFAS(Synthetic aqueous fluids)			
	HFB(water in oil / invert emulsions)	Fair	Good	Good
	HFC(water polymer solutions / water glycols)	Good	Good	Good
	HFDR(phosphate esters)	Fair	Good	Fair
	HFDU(polyol esters)	Good	Very good	Good
Environmentally acceptable hydraulic fluids	HETG(natural vegetable oils)	Very good	Good	Good
	HEES(synthetic esters)	Very good	Very good	Fair poor
	HEPG(polyglycols)	Good	Good	Good
	HEPR(polyalphaolefin)	Very good	Very good	Excellent

Table.2.5.Comparative performances based on thermal, oxidation and hydrolytic stabilities.^[17]

2.3.8. Cost of the fluid

Beside all the properties cost is the important factor both for fluid manufacturers and hydraulic machine producers. Biodegradable hydraulic oil costs three to four times higher than the mineral oil but when longer oil change intervals is considered bio lubricant is equal to mineral and sometimes less because of maintenance of the system. When spill cost is considered mineral oil costs very high for cleaning where no cost for the cleaning the spill of biodegradable hydraulic fluid because the substance is biodegradable.^[20]

2.4. Selection of hydraulic fluid for the system

2.4.1. Effect of viscosity on system performance

The performance of pumps and motors are the important parameters for the overall efficiency of the system. There are two types of hydraulic efficiencies. One is mechanical efficiency and other is volumetric efficiency of the system. Mechanical efficiency relates to frictional losses

in system and volumetric efficiency relates to flow losses in the system. Both of these depend on the viscosity of the fluid.

As shown in the below figure viscosity of fluid is directly proportional to volumetric efficiency and inversely proportional to mechanical efficiency of the system. So fluid should be selected satisfying both these efficiencies for the maximum overall efficiency of the system.

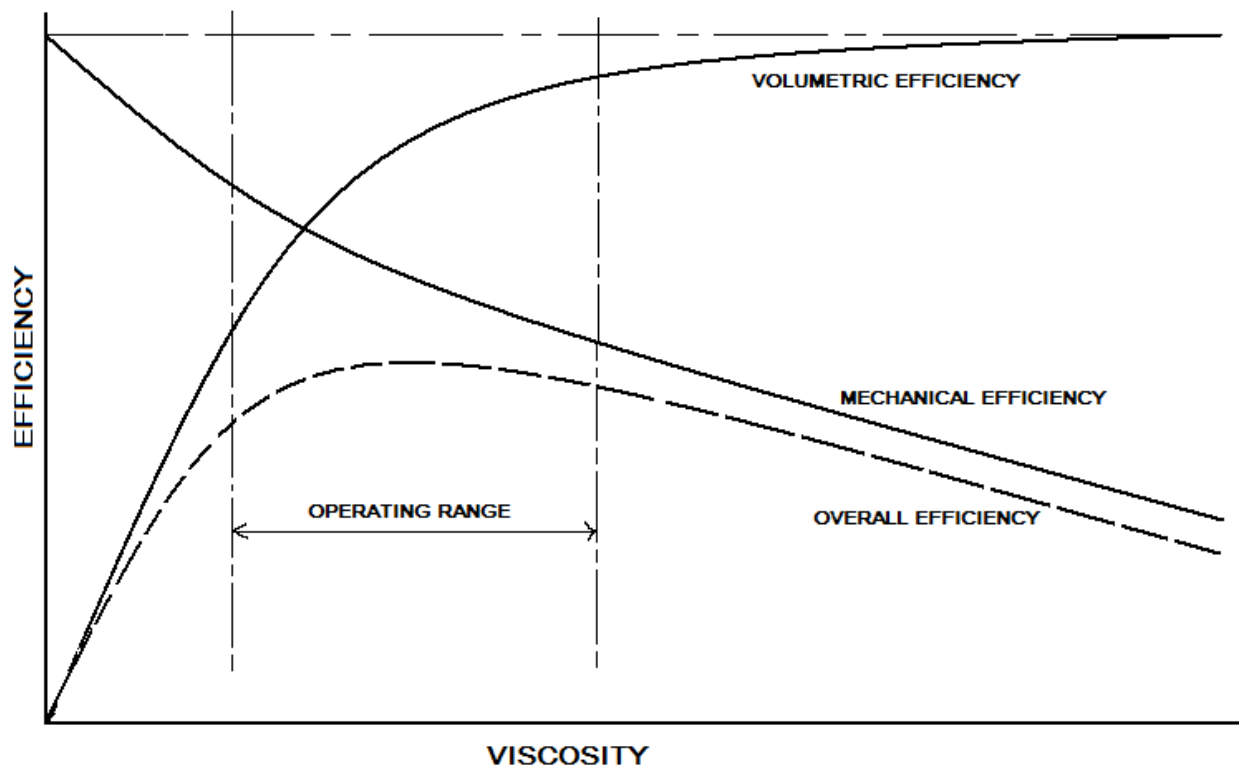


Fig.2.1. Viscosity- efficiency plot.^[21]

2.4.2. Viscosity selection criteria.

The most common method for selecting hydraulic fluid is Temperature Operating Window or TOW method. Based on experimental results majority of the pumps and motors provided satisfactory performance with a minimum of 13 cSt under operating conditions and maximum of 860 cSt during start –up of the system. The below fig is based on calculated temperature for the mid range ISO VG (between 13 cSt to 860 cSt) at 100 VI.^[21]

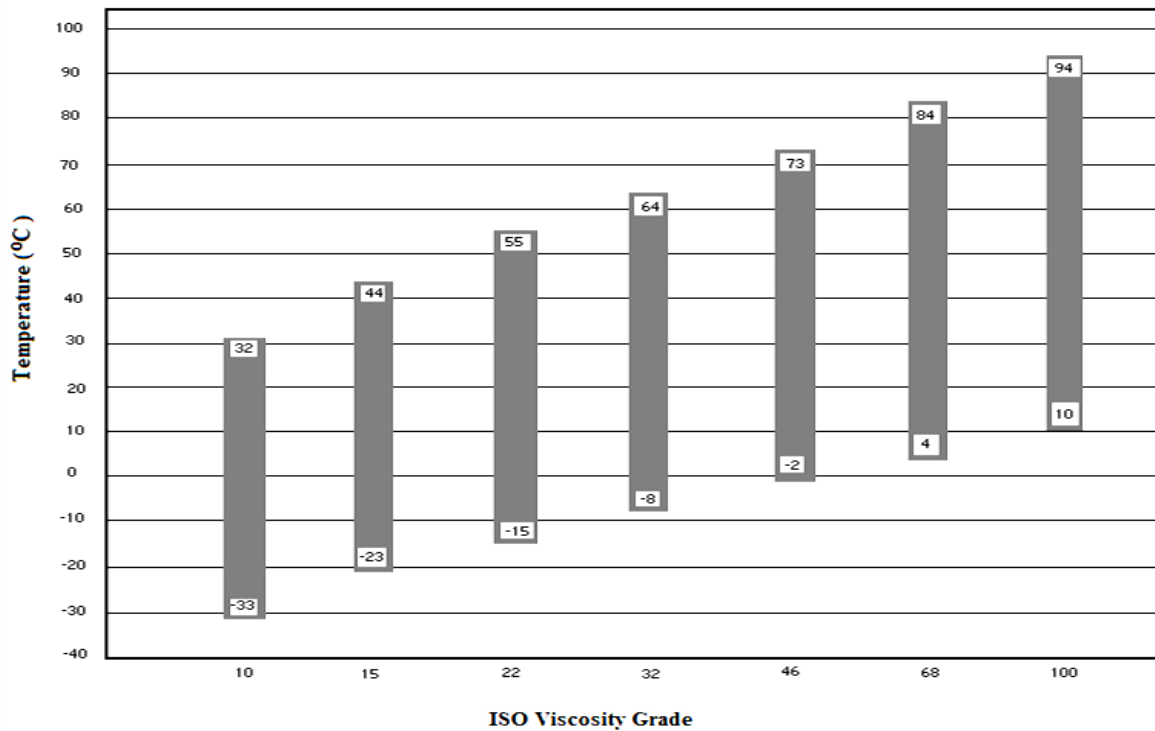


Fig.2.2. TOW plot

While selecting hydraulic fluid by this method, determine the lowest ambient temperature and the highest operating temperature of the system. Then select the fluid that falls in this range of temperature. For example if a hydrostatic transmission is considered, assume that the starting temperature is 0°C and the maximum operating temperature is 50°C. For this range of temperature the suitable ISO VG is 32 VG and 46 VG. Thus any of these viscosity grades can be selected for the hydrostatic transmission.

What if the temperature does not fall in the above fig. i.e TOW method. There is an alternative temperature operating window (ALTOW) method. In this method ASTM D 341 viscosity-temperature chart is used for selecting the viscosity of fluid where it is not explained in this thesis work.

3. Standard test methods

3.1. For hydraulic fluids

It is important to know the specification of the fluid while selecting the fluid for the hydraulic system. Here are some of the important specification and their standard test methods in brief.

3.1.1. Viscosity

This test determines the kinematic viscosity of the hydraulic fluids and liquid petroleum products both opaque and transparent. There are different standards like ISO 3104, ISO 3105, ASTM D445, ASTM D446, IP 71, DIN 51366, BS 188 to measure kinematic viscosity. All these standards use nearly the same method to test kinematic viscosity. For this test method glass capillary viscometer is used to determine the kinematic viscosity. In this the time is calculated for the fluid to fall under its own gravity from one point to another at constant temperature and then it is multiplied by viscometer constant to get kinematic viscosity in centistokes. The viscosity is measured minimum at two different temperatures mostly at 40°C and 100°C, so that viscosity index of the fluid can be calculated.^[22]

3.1.2. Total acid number (TAN)

Total acid number is the presence of milligrams of potassium hydroxide (KOH) per gram of sample. This TAN indicates the potential of corrosion problems. ISO 6618, ASTM D664 and ASTM D974 are some of the standard methods. In ISO 6618 'colour indicating titration' method is used to measure the acid number where an appropriate pH colour indicator is added to the sample. The volume of colour titrant that is added to change the colour of the sample permanently is used to calculate acid number.^[23]

3.1.3. Flash point

Flash point is the minimum temperature at which the fluid vaporize to form ignitable mixture in air when fire is brought over this mixture. The standard methods are ISO 2592, ASTM D92. In these two standards 'Cleveland open cup method' is used to determine flash point. For this the Cleveland apparatus is filled with fluid and then its temperature is increased rapidly at first and then slowly till it reaches its theoretical flash point. Then a small fire is brought over the apparatus, therefore the minimum temperature at which the mixture ignites is considered as flash point.^[24]

3.1.4. Pour point

The pour point is the minimum temperature at which the fluid becomes semi-solid and loses its fluidity. There are different test standards for different types of fluid, for example ISO 3016 for the petroleum products. Other standards are ASTM D97, ASTM D 2500 etc. The general procedure for petroleum products is the fluid is cooled to form paraffin crystals. Then the temperature is maintained at above 9°C above the expected pour point. For every subsequent 3°C temperature the apparatus is tilted to check the surface. If there is no movement in fluid then the apparatus is kept horizontal for 5 seconds. If the fluid does not flow then it is considered as pour point.^[25]

3.1.5. Water content

This test is used to determine the water content in the fluid. Water in fluid is the main problem that decreases viscosity and forms rust. So the user has to check whether the fluid is suitable for the machine with that water content. Some of the standard tests are ISO 12937 and ISO 6296 which uses 'Karl Fischer titration method' to find water content.^[26]

3.1.6. Air release

Air release property is important parameter to be considered mainly in the systems where residue time is short because the air flows with fluid causes pressure losses in the system. Some of the standard test methods are ISO 9120, ASTM D3472, IP 313 and DIN 51381 where air is blown into the fluid and the time taken by the air to decrease its volume by 0.2 % at constant temperature is considered as air release time.^[27]

3.1.7. Low temperature fluidity

This test determines the highest possible viscosity of fluid at very low temperature for a certain period of time. This is useful for the system when it is stand still for long time at low temperature. The standard test method is ASTM D2532.^[28]

3.1.8. Elements by ICP

This test is used to determine the additive elements in the fluid. This test provides wear indication of the hydraulic machines by testing used oil. 'Inductively Coupled Plasma (ICP) Atomic Emission Spectrometry' is used to determine the elements and it can measure the elements down to 0.1 parts per million. ASTM D5185 and ASTM D4951 are the standard tests.^[29]

3.1.9. Oxidation stability

This test is used to determine the oxidation stability of the fluid. The standard tests are ASTM D943 and DIN 51554-3. In DIN 51554-3, 70 ml of oil is kept at 95°C for 35 days in atmospheric oxygen and it is stirred with glass stirrer connected to copper strip at a speed of 24 stirs per minute. Then the viscosity, acid number and other parameters are measured for every week.

3.1.10. Hydrolytic stability

There are more chances of fluid to get contaminated with water which decreases viscosity, forms rust that decrease the performance of the system. So it is important to know the hydrolytic stability of the fluid. The ASTM D2619 is the standard test method where 75 g of fluid, 25 grams of water and a copper strip is sealed in vessel and stirred at 5 rpm for 48 hrs at 93°C. Then the acid number and viscosity is measured to find the hydrolytic stability.

3.1.11. Thermal stability

The effect of temperature on the metals is also an important factor. The ASTM D2070 is the standard test method in which copper and steel rods are placed in the oil at a temperature of 135°C for one week. Then the condition of the metal specimens is noticed and viscosity of fluid is also measured.

3.1.12. Shear stability

This test is used to evaluate the shear stability of the hydraulic fluid in terms of permanent loss of viscosity of the fluid by irradiating a sample of fluid by using sonic oscillator. ASTM D5621 – 07 is the standard test method.

3.2 For fluid power components

3.2.1. Pumps^[30]

Pump is the core component for the fluid power system. So it is important to know the performance of the pump at different working conditions. To know the performance volumetric and mechanical efficiency of the pump should be measured.

To test the pump

1. Inlet pressure of the pump should be kept constant.

Record the measurements of

1. Input torque.
2. Outlet flow of the pump.
3. Fluid temperature.
4. Drainage flow (if needed)

Now test the pump

1. At constant speed and by varying the outlet pressure of the pump.
2. By varying the speed of the pump at constant pump outlet pressure.

By using these two tests calculate the efficiencies of the pump by the following equations

$$\eta_{hmp} = \frac{\epsilon_p D_p \Delta p}{2\pi M_{in}} [1] \quad \eta_{volp} = \frac{q_{ep}}{\epsilon_p D_p n_p} [1]$$

Where η_{hmp} = hydromechanical efficiency of pump.

ϵ_p = displacement setting of the pump.

D_p = Displacement of the pump.

Δp = pressure difference of the pump.

M_{in} = input torque to pump.

η_{volp} = volumetric efficiency of the pump.

q_{ep} = effective flow of the pump.
 n_p = speed of the pump.

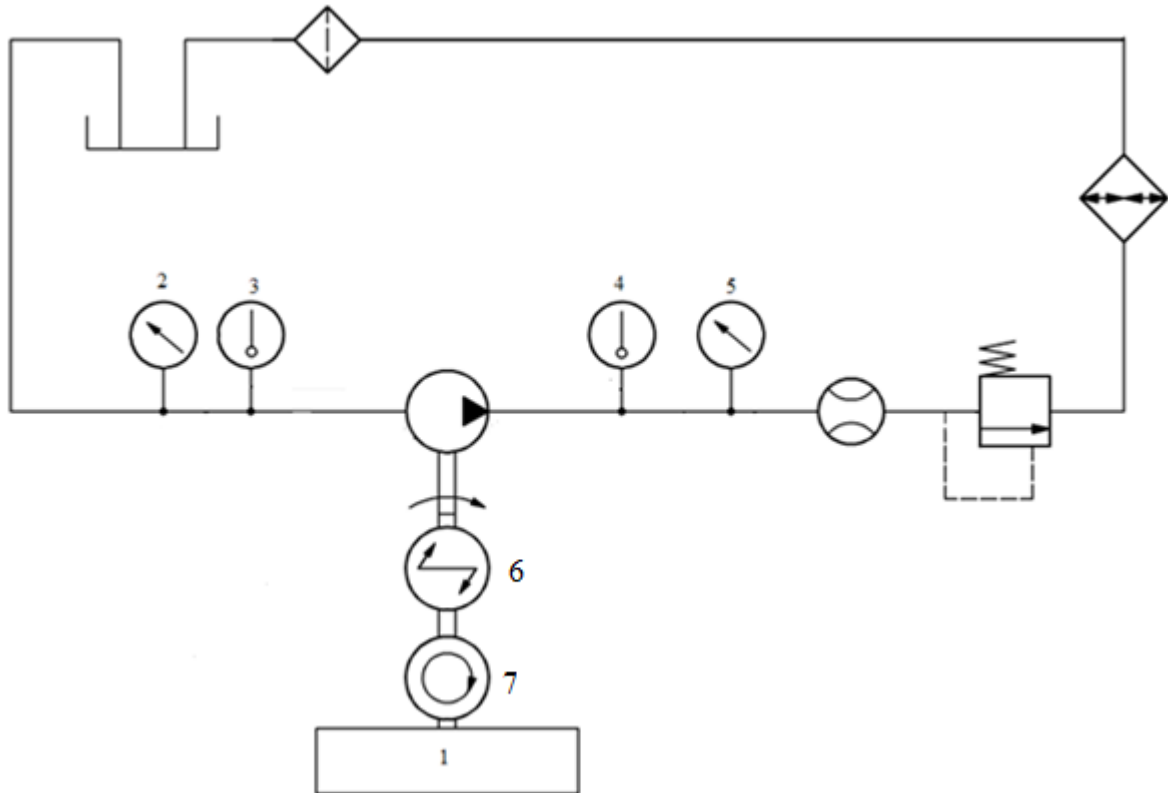


Fig.3.1. Test circuit of the pump (open circuit) showing positioning of sensors. 1) Driver, 2) & 5) Pressure transducers, 3) & 4) Temperature sensors 6) Torque meter 7) Speed meter.

The standard positioning of sensors in any test circuit should be in such a way that.

1. Temperature sensors should be placed at a distance of $2d$ to $4d$ from the component to be measured both in upstream and downstream. Where 'd' is the diameter of the hose or pipe.
2. Pressure transducers should be placed at a distance of minimum of $5d$ upstream and minimum of $10d$ downstream.

3.2.2. Motors ^[29]

To test the motor the outlet pressure of the motor should be kept constant.

Record the measurements of

1. Inlet flow to motor.
2. Output torque.
3. Fluid temperature
4. Drainage flow (if needed).

Now test the motor over the entire speed range of the motor by varying the flow to the motor and at different input pressures.

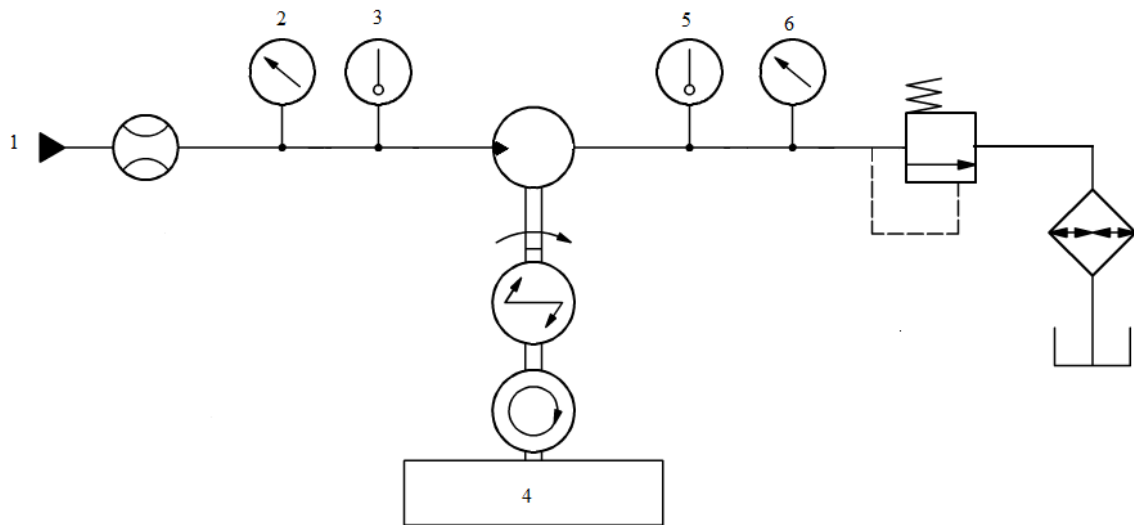


Fig.3.2. Test circuit of the motor. 1) Regulated flow supply, 2) & 6) Pressure transducers, 3) & 5) temperature sensors, 4) Load.

Note for pumps and motors:

1. Temperature of the fluid should be maintained as stated by the manufacturer with a ISO temperature tolerance ^[a] not more than $\pm 4^{\circ}\text{C}$.
2. All the variables like outlet pressure range, speed etc should be within the range, as stated by manufacturer.
3. If the pump or motor is variable displacement then the displacement setting should be set according to the requirement.
4. If it has to be tested for reverse flow, follow the same procedure.

3.2.3. Transmission ^[29]

The following measurements can be recorded at a specific pump speed

1. Input torque
2. Output torque
3. Output rotational speed.
4. Fluid pressure
5. Fluid temperature where it is required.

Now test the system

1. For entire power (product of pressure and flow at any given point) range within the limits as specified by the manufacturer at specific input speed.
2. At different input speed within the limits.

^a There are three classes of temperature tolerances according to ISO standards. They are $\pm 1^{\circ}\text{C}$, $\pm 2^{\circ}\text{C}$ and $\pm 4^{\circ}\text{C}$.

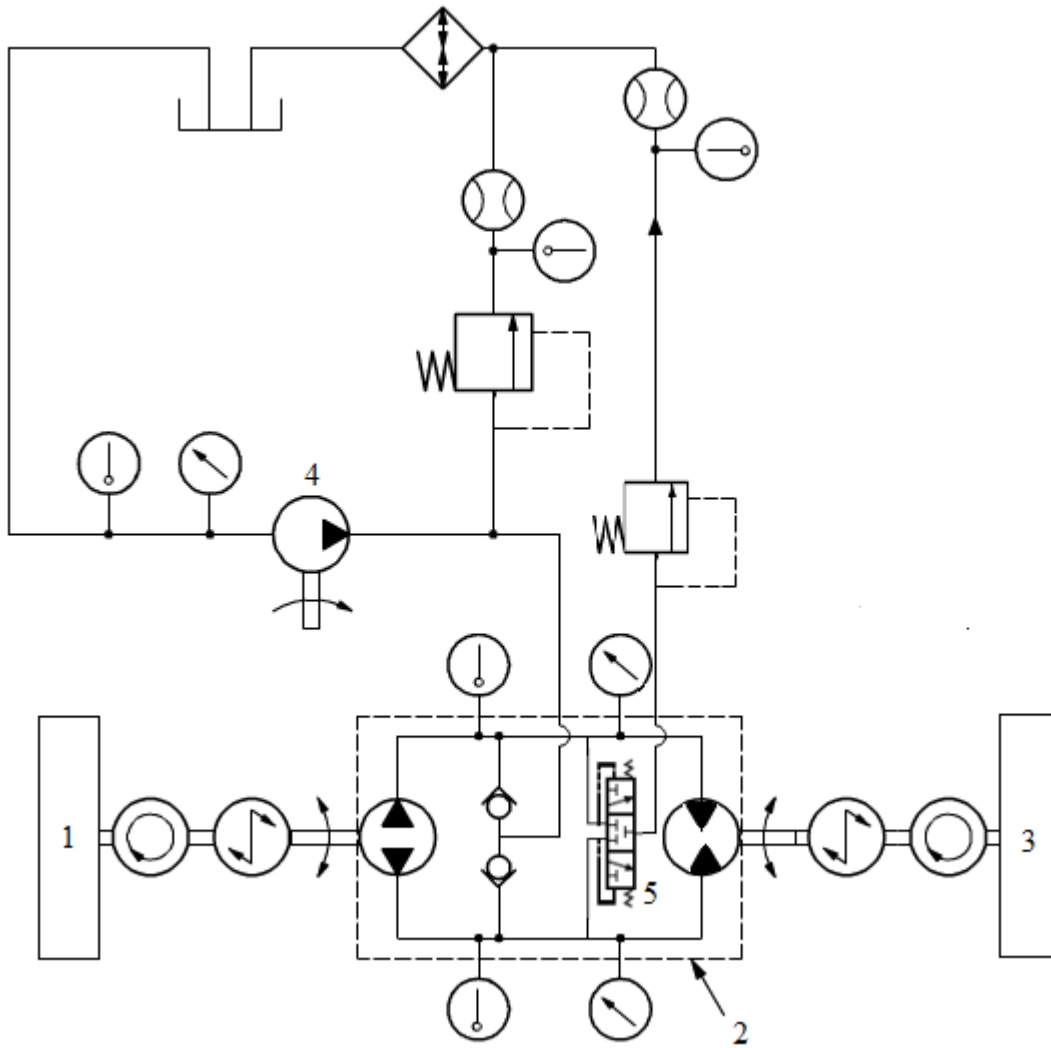


Fig.3.3. Test circuit of the transmission. 1) Driver, 2) Transmission, 3) Load, 4) Boost pump, 5) Cooling valve.

Note:

1. If the pump is variable displacement, record the same measurements at 75%, 50% and 25% of the pump maximum displacement settings and with maximum motor displacement setting.
2. If the motor is variable displacement, record the same measurements with minimum motor displacement setting.

3.2.4. Valves - determination of pressure difference ^[31]

The hydraulic valves control the direction and flow rate of the flow. In this process there is some resistance to flow which results in pressure loss. This can be determined by the standard test procedure.

To test the valve the valve circuit should be in such a way that

1. The flow should be controllable.
2. A pressure relief valve to relieve excess pressure should be used before the valve.

3. A uniform tube length of at least $5d$ should be placed between upstream pressure transducers and the valve.
4. A visibly uniform tube of length $10d$ should be used between valve and downstream pressure transducer to maintain steady state flow.
5. A uniform tube length of $5d$ should be placed between downstream pressure transducer and temperature sensor and from temperature sensor to flow meter.
6. The sensors should be calibrated with a maximum error of $\pm 3\%$ for flow meter, $\pm 5\%$ for pressure difference and ± 2 kelvin for temperature.
7. The maximum temperature tolerance is ± 4 kelvin.

Then the pressure difference can be made by varying the flow by keeping temperature constant.

Note: 'd' is inside diameter of the valve.

4. Experimental test bench and simulation model

The test bench consists of tank, external gear pump, electric motor, hose, pressure relief valve, variable orifice, cooler, flow metre, pressure and temperature transducers and other accessories for connections. The specifications of the system are explained in detail below.

4.1. System description

The system is a simple model as shown in **fig.4.1** with electric motor is mounted above the tank and pump is connected to electric motor which comes inside the tank that is not visible in actual system. One end of the hose is connected to the outlet of the pump and other end to pressure relief valve which acts as load in this system. One end of the cooler is connected to pressure relief valve and other end to the tank. A variable orifice is connected between pump outlet (or) inlet of hose and other end to cooler, so that by adjusting the flow in orifice flow through hose can be varied.

Flow metre is fixed to inlet of hose to measure flow. Two pressure transducers are fixed at both ends of the hose to measure pressure losses in the hose. Temperature sensor is fixed at inlet of hose to measure the temperature of the oil. Signals from the sensors of the system was taken by using multimeter.

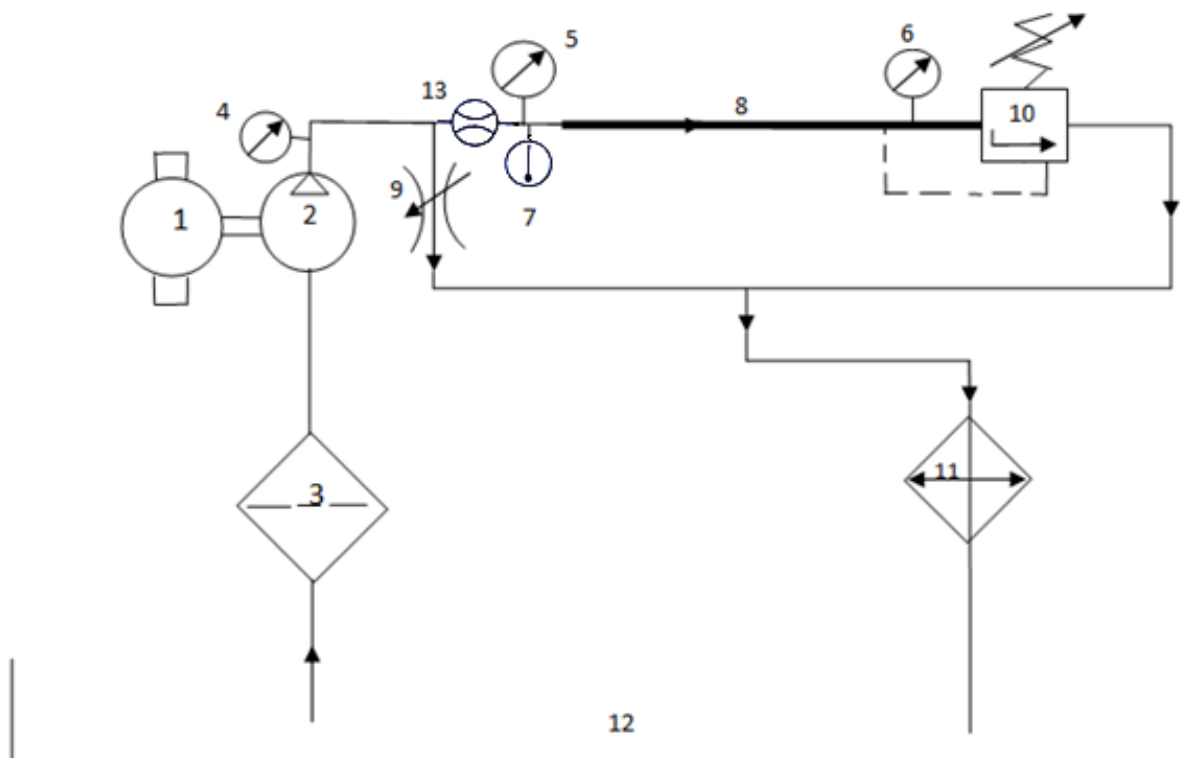


Fig.4.1. Schematic diagram of experimental test bench

1.Electric motor; 2.Fixed displacement pump; 3.Filter; 4,5,6.Pressure transducers; 7. Temperature sensor; 8.Hose; 9.Variable orifice; 10.Pressure relief valve; 11.Cooler; 12.Tank; 13. Flow meter.

4.2. System component specifications

4.2.1. Electric motor

Nominal speed	1440 rpm
Power	7.5 kw

4.2.2. Hydraulic pump

Type of pump	External gear pump (from Marzocchi)
Displacement	35.2 cc/rev
Maximum pressure	155 bar
Maximum speed	2500 rpm

4.2.3. Pressure relief valve

Maximum pressure	350 bar
Maximum flow	400 l/min

4.2.4. Pressure transducers

Transducer 1	0-350 bar/ 0-10 v
Transducer 2	0-200 bar/ 0-10 v

4.2.5. Temperature sensor

0-100 °C / 0-10 v

4.2.6. Hose

All the equipment is already provided except hose. So the diameter of hose is an important parameter for the system. Calculations are made to know at what diameter the flow enters into turbulent. The calculation of diameter is as follows.

Reynolds number (Re) :

Reynolds number is a unit less value by which we can determine whether the flow is turbulent or laminar.

If $Re < 2300$ it is laminar flow

$Re > 2300$ it is turbulent flow

$$Re = \frac{d \cdot V \cdot \rho}{\mu} \quad [1] \quad (\text{or}) \quad Re = \frac{d \cdot V}{\nu}$$

V = fluid velocity [m/s]

d = diameter of the hose

ρ = density of the fluid [kg/m^3]

μ = dynamic viscosity of the fluid [Ns/m^2]

ν = kinematic viscosity of the fluid [m^2/s]

Fluid velocity:

$$V = \frac{Q}{A} \quad (\text{since } Q = AV)$$

Where Q = Fluid flow [m^3/s]

A = Area of the hose [m^2]

By using both Reynolds number and velocity of the fluid graph has been plotted between diameter of the hose and Reynolds number with the following pump specifications given by manufacturer.

Speed of the pump = 1440 rpm

Displacement of the pump = 35.2 cc/rev

Pump flow = 50.688 L/min

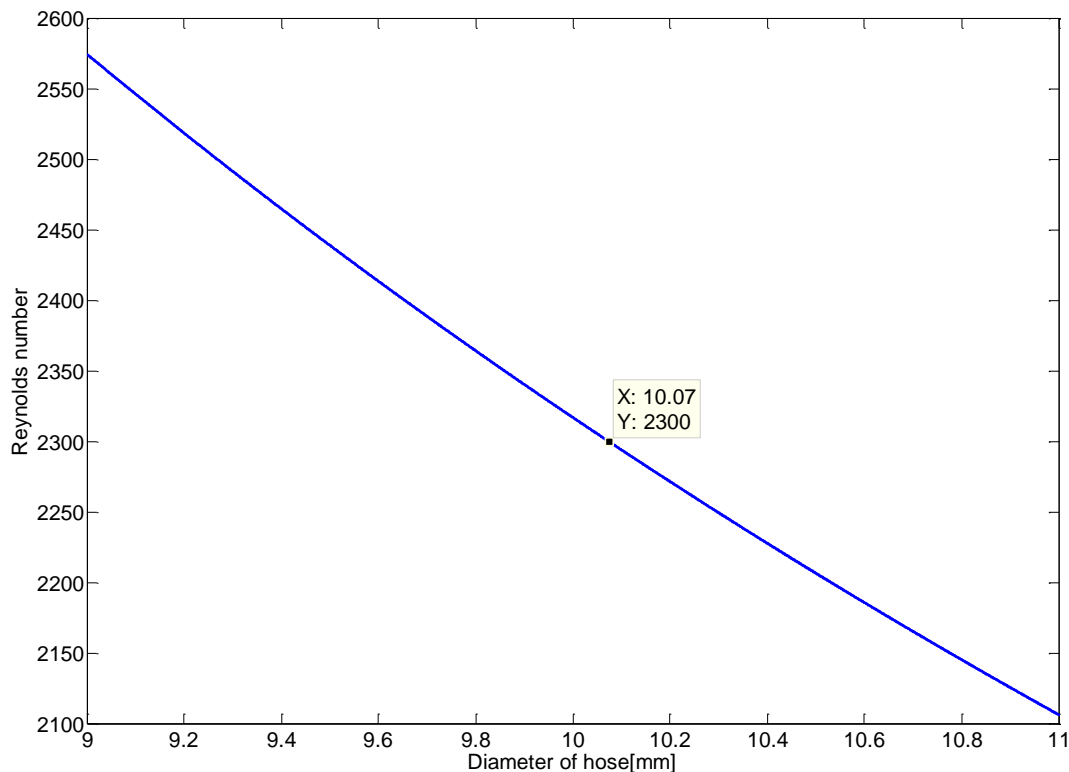


Fig.4.2. Reynolds number against Diameter of the hose

The **fig.4.2** shows that the turbulent flow can be created when the diameter of hose is below 10.07 mm. So a hose of diameter 10 mm from **hydroscand** with a length of 15 m has been selected. This is for the standard fluid ISO VG 46 at maximum flow. Since other fluids have lower viscosities at 40°C than this standard one, the pressure losses can be analysed at both laminar and turbulent flow for the remaining fluids and this fluid at higher temperatures. The pressure losses in hose differs in straight hose compared to bend hose. So it is important to know that how far the pressure losses differs in hose for straight one compared to bent. So the simulations were made to know the difference as it is explained in next section.

The flow of the pump is varied from 0 to maximum flow 50.688 L/min by using the ramp signal given to the electric motor. The results of the three models are shown in the below graph. The standard *mineral oil 46* at 40°C has been used for all three simulation models.

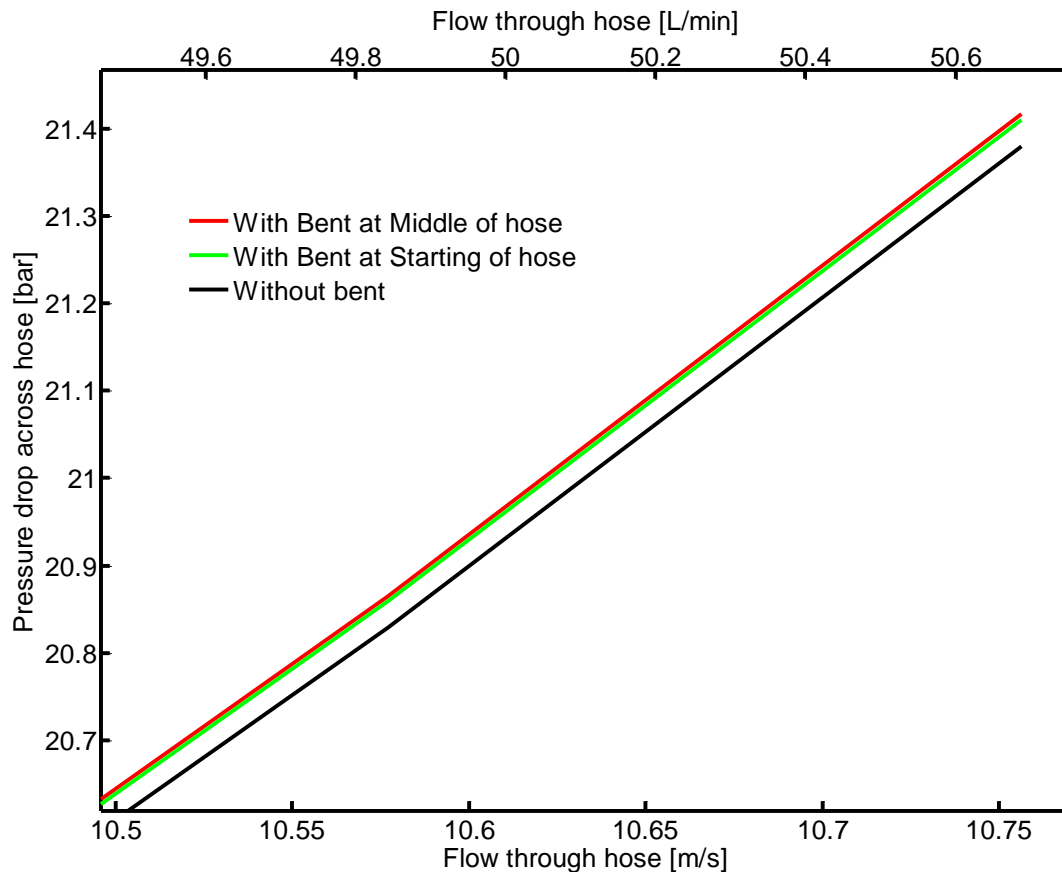


Fig.4.6. Simulation results of three models showing Flow Vs Pressure drop in hose.

From the **fig.4.6** it is noticed that the difference in pressure loss among three models is very small and it will not vary much in test bench too. So the model with straight hose is considered for the test bench to measure the actual pressure losses in the hose.

5. Test procedure and results

5.1 Types of tests

Three types of tests are conducted on each fluid to measure

5.1.1. Pressure losses in hose

By varying the flow through hose, pressure losses in the hose can be measured by subtracting the pressures from pressure transducers at positions 5 and 6 as shown in **fig.4.1**. Variable flow through hose has been achieved by adjusting the flow through orifice at position 9 as shown in **fig.4.1**. Since pressure drop in hose also depends on the viscosity of the fluid the measurements are repeated at four different temperatures that is at 30°C, 40°C, 50°C and 60°C with ISO class 3 temperature tolerance of maximum $\pm 4^\circ\text{C}$, where temperature is inversely proportional to viscosity. Pressure drop in hose is measured at 8 to 10 different flows depending on the type of fluid and temperature. Temperature of the fluid was controlled by using cooler.

5.1.2. Volumetric efficiency of the pump

By varying the load on the pump the flow of the pump varies according to the equation in section 1.4. The pressure on the pump is varied by using pressure relief valve at position 10 in **fig.4.1** at full flow of the pump that is at 1440 rpm and by completely closing the variable orifice. Flow is measured by using flow meter at position 13 in **fig.4.1**. So as the pressure on the pump increases the gears in the pump compensates and flow decreases. Since the flow of the pump also depends on the viscosity of the fluid the measurements are repeated at 4 different temperatures that is at 30°C, 40°C, 50°C and 60°C with ISO class 3 temperature tolerance of maximum $\pm 4^\circ\text{C}$. The flow is measured at 15 to 25 different loads depending on the type of fluid and temperature.

5.1.3. Time taken to rise the temperature

By keeping the pump pressure constant at 50 bar with full flow time has been measured to rise the temperature from 40°C to 60°C. The results are in **Table.5.1**.

It is observed that the temperature rises quickly in the fluids with lower viscosity than the fluids with higher viscosity. This may be due to higher leakages in the pump where it takes more time to cool the oil when travelling through hose. It also depends on the specific property of the fluid.

S.No	Type of fluid	Time [seconds]
1	Diesel oil	666
2	Synth 12	604
3	Synth 32	968
4	Synth e 32	1102
5	Synth es 32	1068
6	Mineral oil 46	1056

Table.5.1. Time taken to rise the temperature.

5.2. Comparing with simulation results

The simulation model in **fig.4.3** is used to compare the measured pressure losses in hose with the simulation models. The input parameters given to the simulation model are dynamic viscosity, density and temperature of the oil. The simulation results are close to the measured ones when the flow is turbulent but there is a large difference when the flow is laminar which are clearly noticeable in figures **5.3,5.4,5.5** and **5.6**. When the flow is changing from laminar to turbulent in simulation plot there is a curved profile, this may be because the simulation model adjusts the viscosity of the fluid accord to pressure losses in hose. Here the plots are shown only at 50°C of oil. The remaining plots at temperatures 30°C, 40°C and 60°C are in appendix section 10.2.

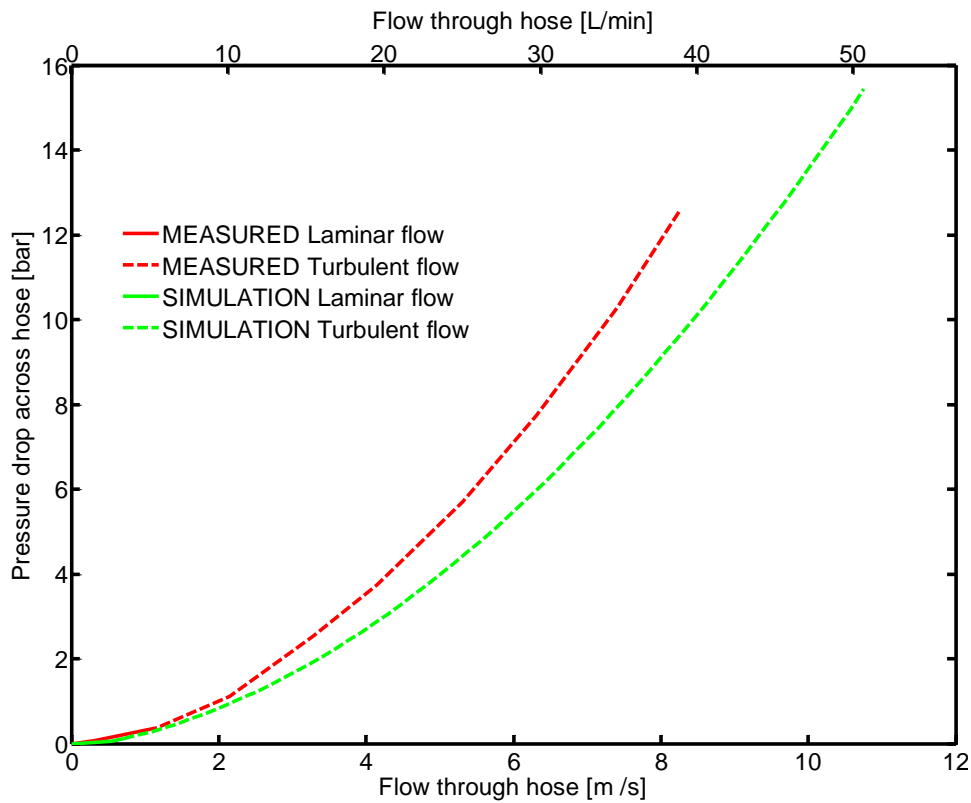


Fig. 5.1. Flow Vs Pressure drop across hose of diesel oil at 50°C

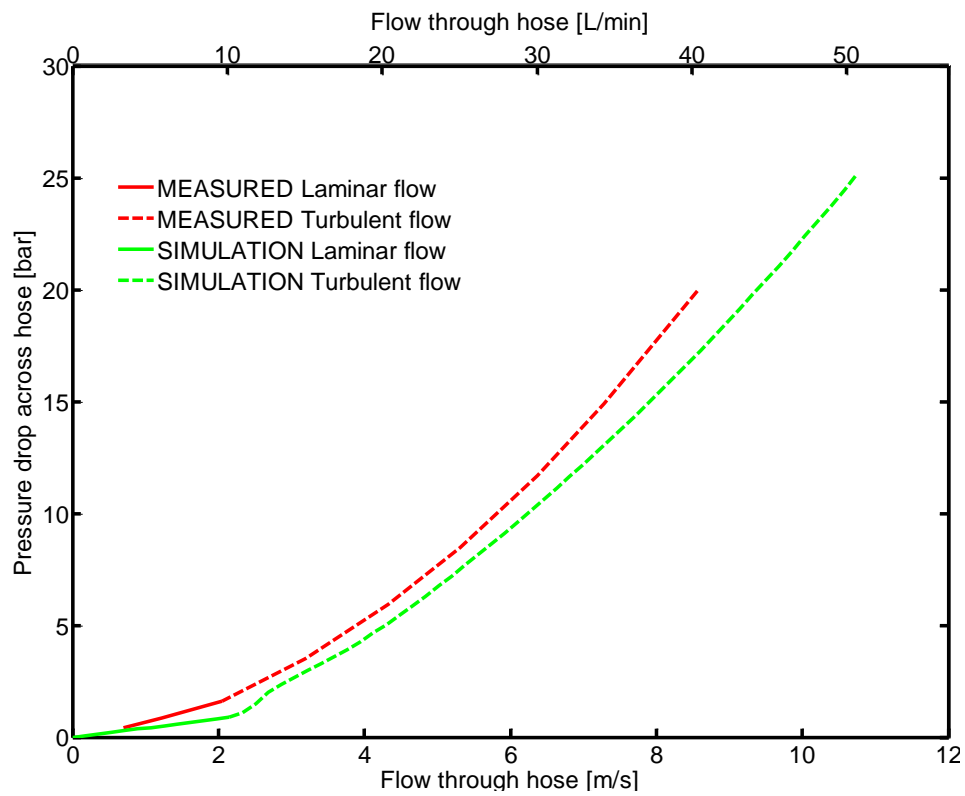


Fig. 5.2. Flow Vs Pressure drop across hose of synth 12 at 50°C

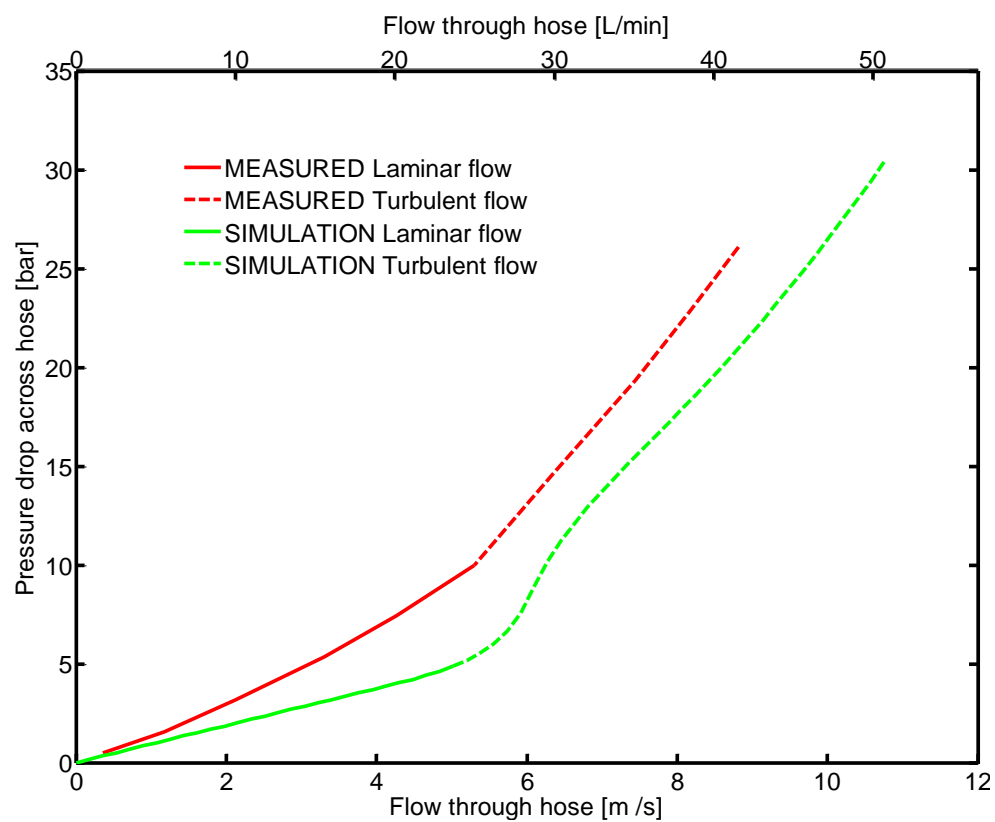


Fig. 5.3. Flow Vs Pressure drop across hose of synth 32 at 50°C

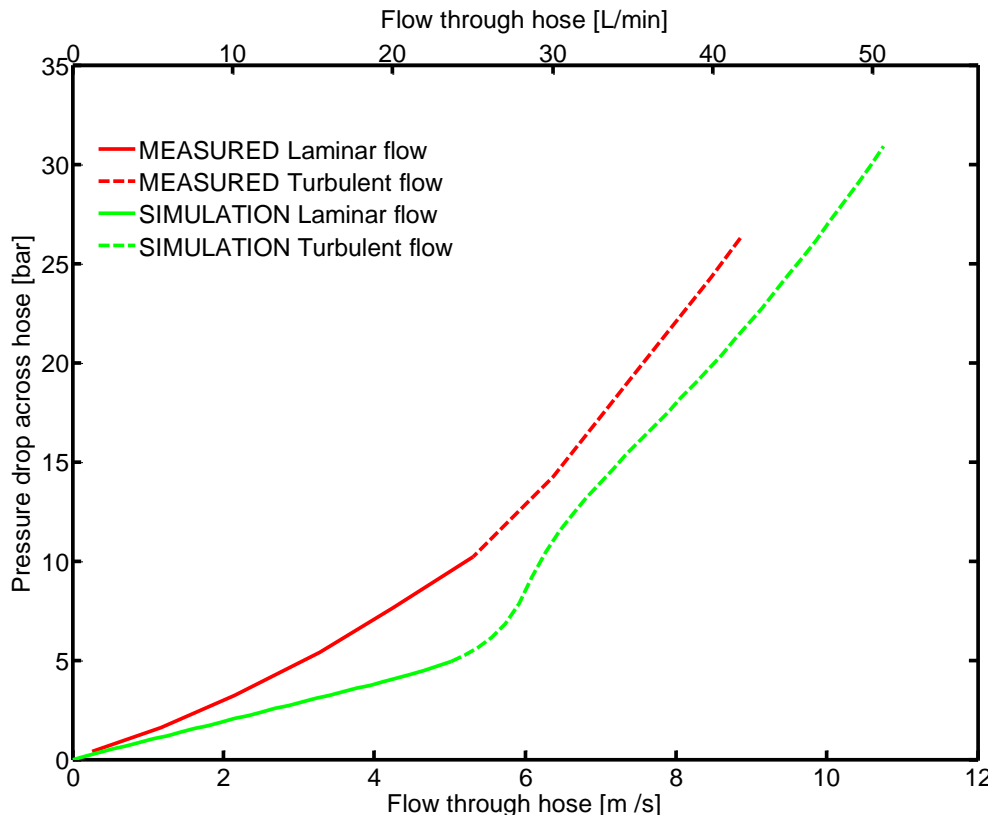


Fig. 5.4. Flow Vs Pressure drop across hose of synth e 32 at 50°C

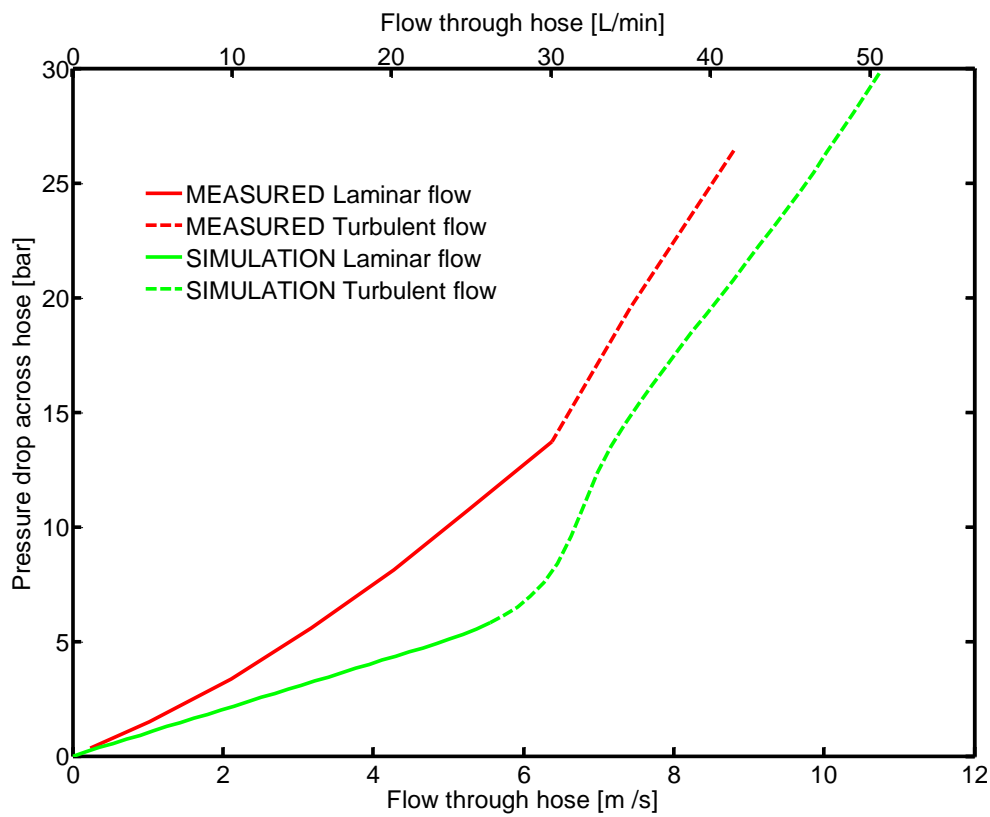


Fig. 5.5. Flow Vs Pressure drop across hose of synth es 32 at 50°C

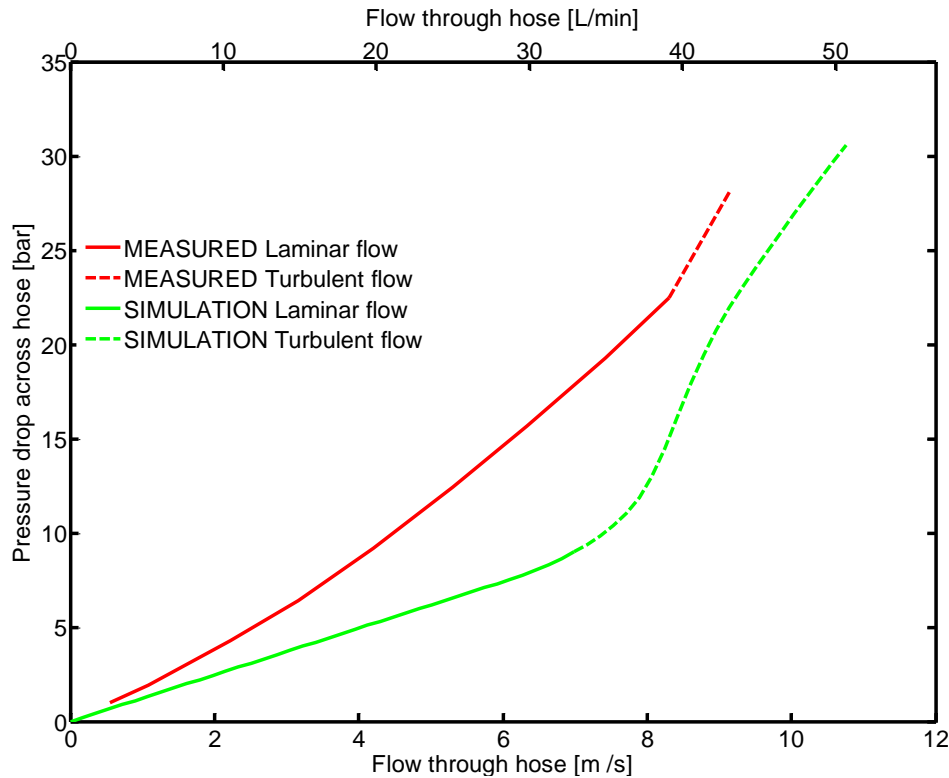


Fig. 5.6. Flow Vs Pressure drop across hose of mineral oil 46 at 50°C

5.3. Comparative performance of all fluid on hose at constant temperature

The pressure losses for the fluids **synth 32**, **synth e 32** and **synth es 32** are almost equal with negligible difference at both laminar and turbulent flows but the turbulence in **synth es 32** occurs at higher flows as it is noticeable in **fig.5.8** and **fig.5.9**. When the above three fluids are compared with the standard **mineral oil 46** the pressure losses in hose are almost equal when the flow is turbulent. The pressure losses in **diesel oil** and **synth 12** are very low when compared to **mineral oil 46** and this is due to its lower viscosity and the losses are constant at all the operating temperatures because of its high viscosity index. The laminar and turbulent flows are calculated based on the viscosity taken from **viscosity temperature** chart and density by using online calculator. The individual fluid pressure losses in hose at different temperatures are in appendix section 10.1.

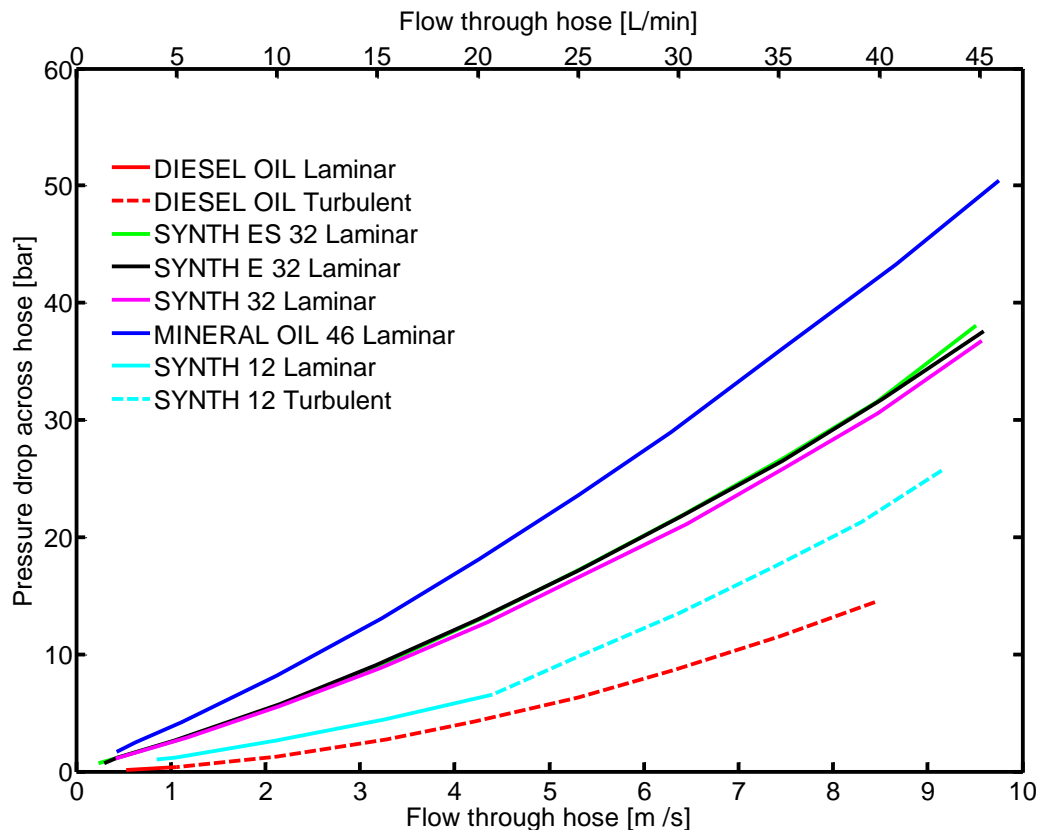


Fig. 5.7. Flow Vs Pressure drop across hose at 30°C

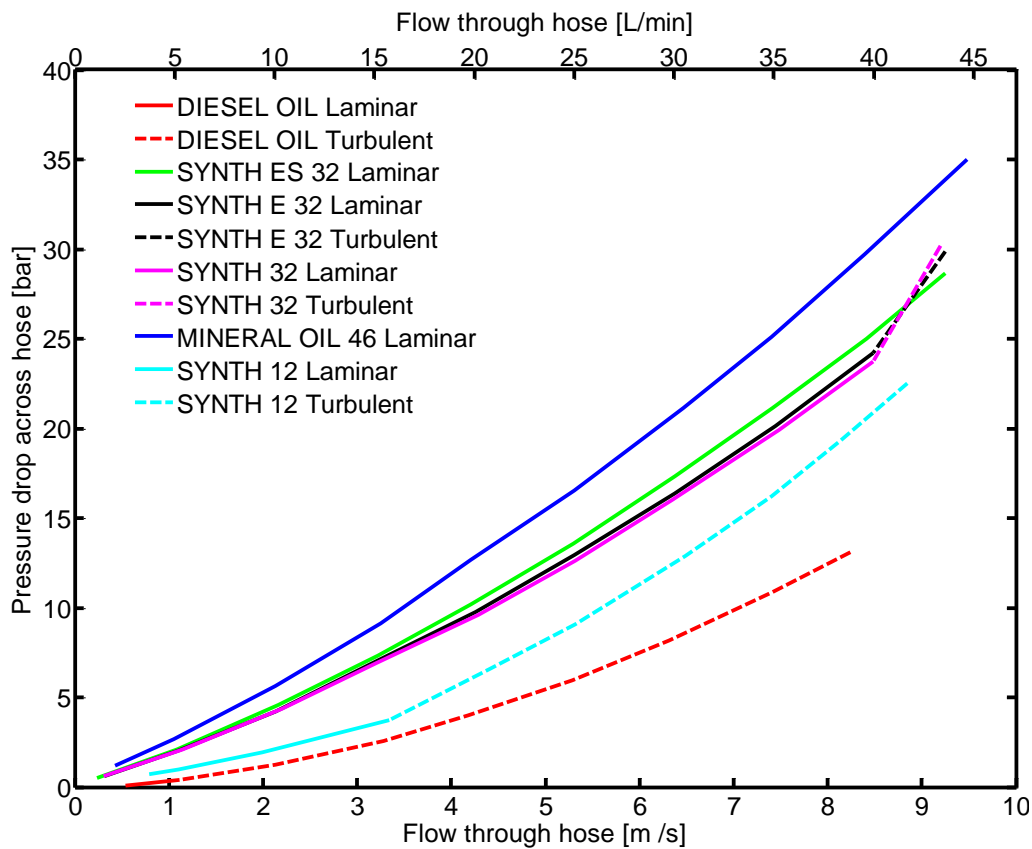


Fig. 5.8. Flow Vs Pressure drop across hose at 40°C

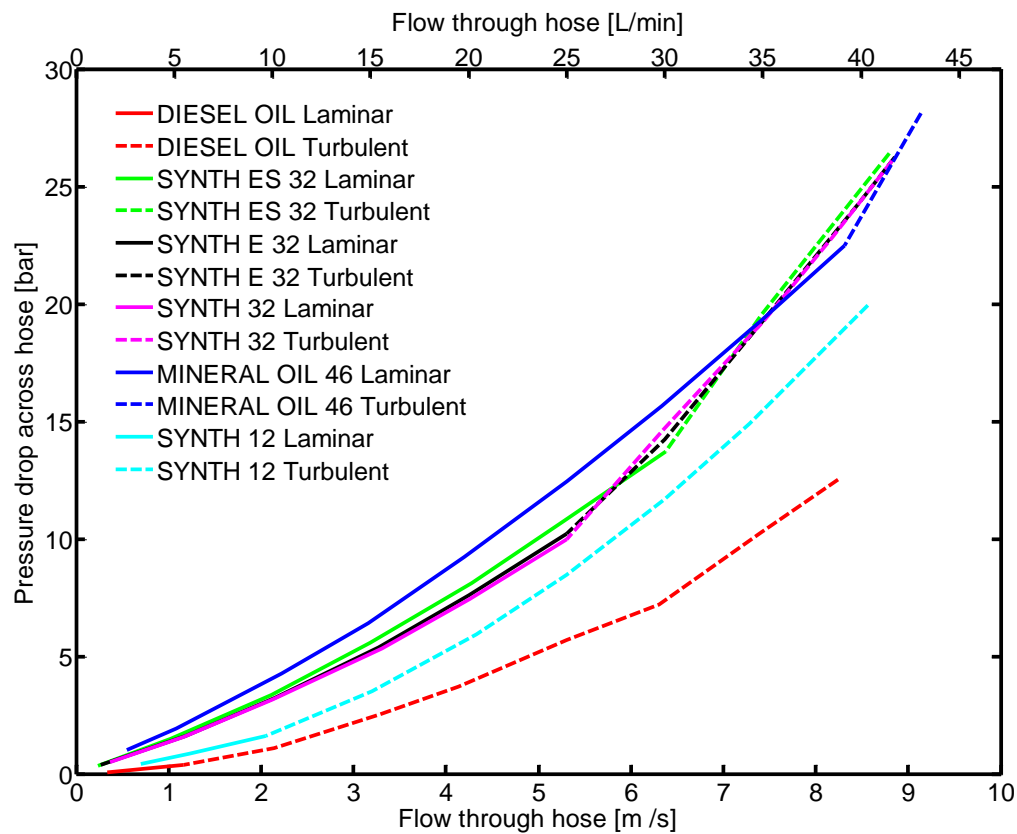


Fig. 5.9. Flow Vs Pressure drop across hose at 50°C

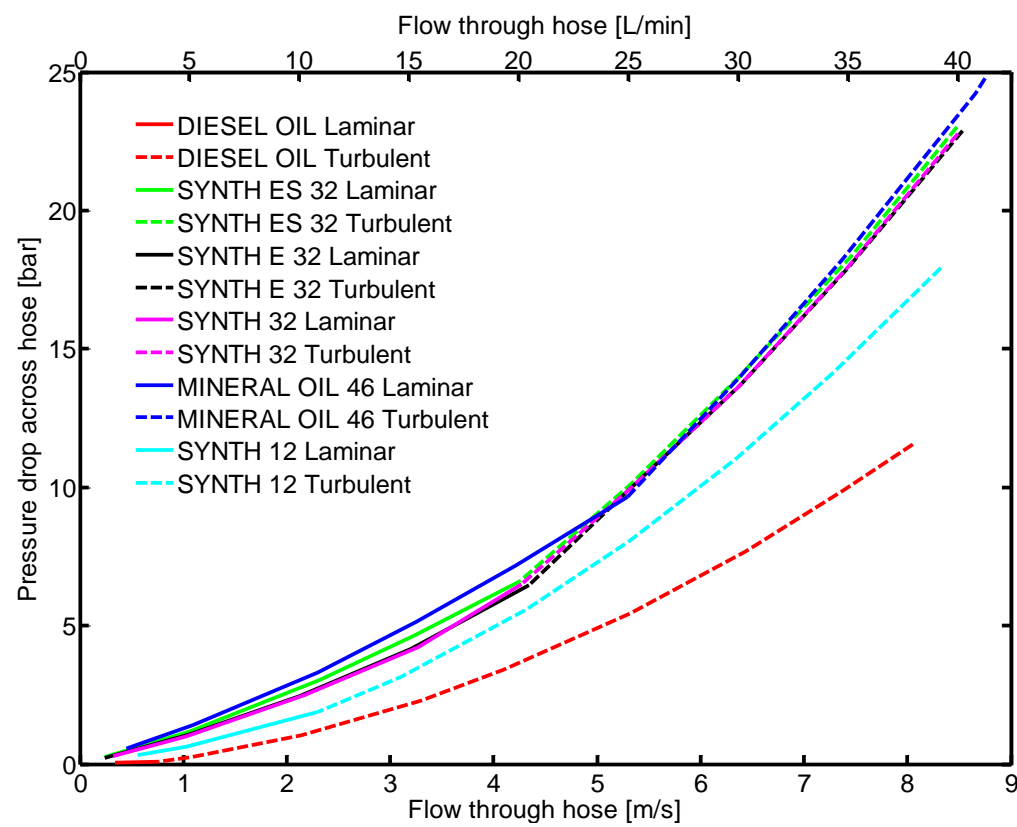


Fig. 5.10. Flow Vs Pressure drop across hose at 60°C

5.4. Comparative performance of all fluids on pump at constant temperature

It is difficult to measure the flow of the pump at lower pump pressures due to system complications. So the flow of the pump is calculated by interpolations based on the measured values. The pressure of the pump during testing of **diesel oil** is not increased beyond 90 bar because of the safety reasons but it can be predictable at higher pressures. From the plots it is noticed that the pump flow losses of the three **synth 32** fluids are getting close to **mineral oil 46** as the temperature increases. That means the pump losses for these **synth 32** fluids are almost constant as the temperature varies. When flow losses in pump of **diesel oil** and **synth 12** are considered, the losses are quite high. This is because of its lower viscosities but losses are constant at all the temperatures because of its higher viscosity index. The individual fluid pump flow losses at different temperatures are in appendix section 10.1.

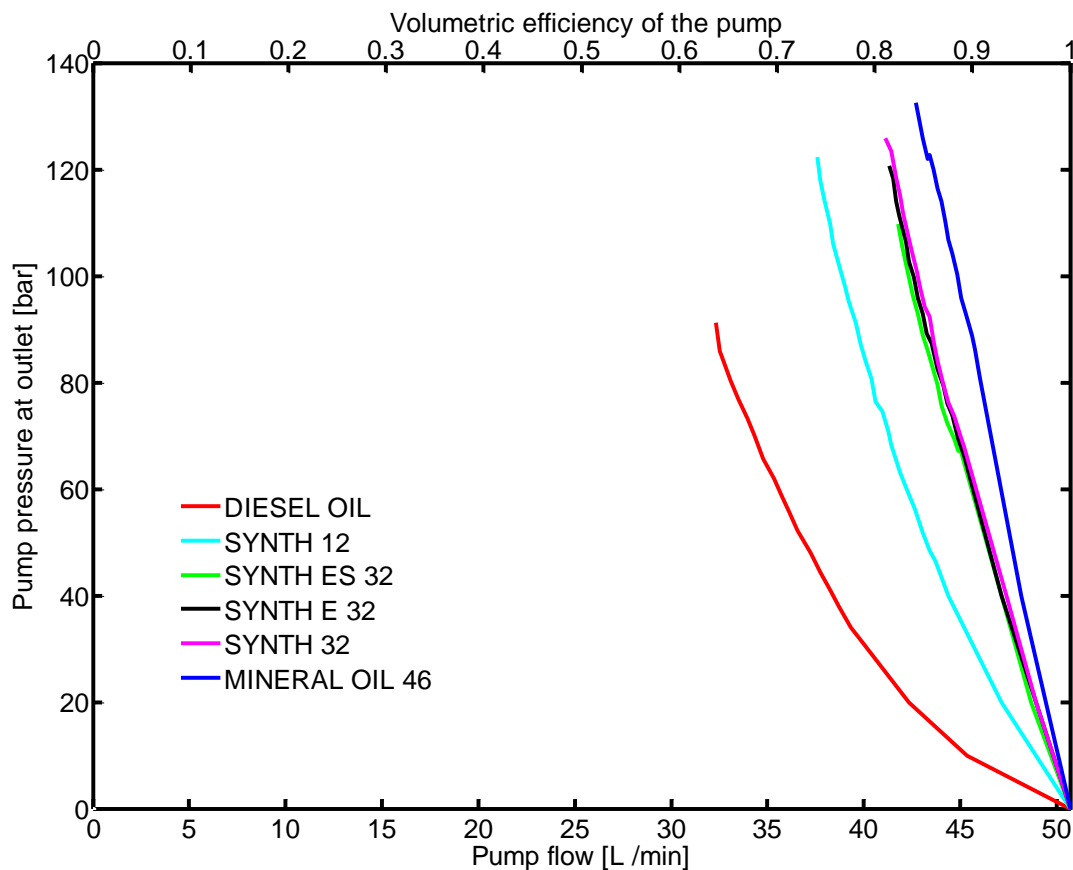


Fig. 5.11. Flow Vs Load on the pump at 30°C

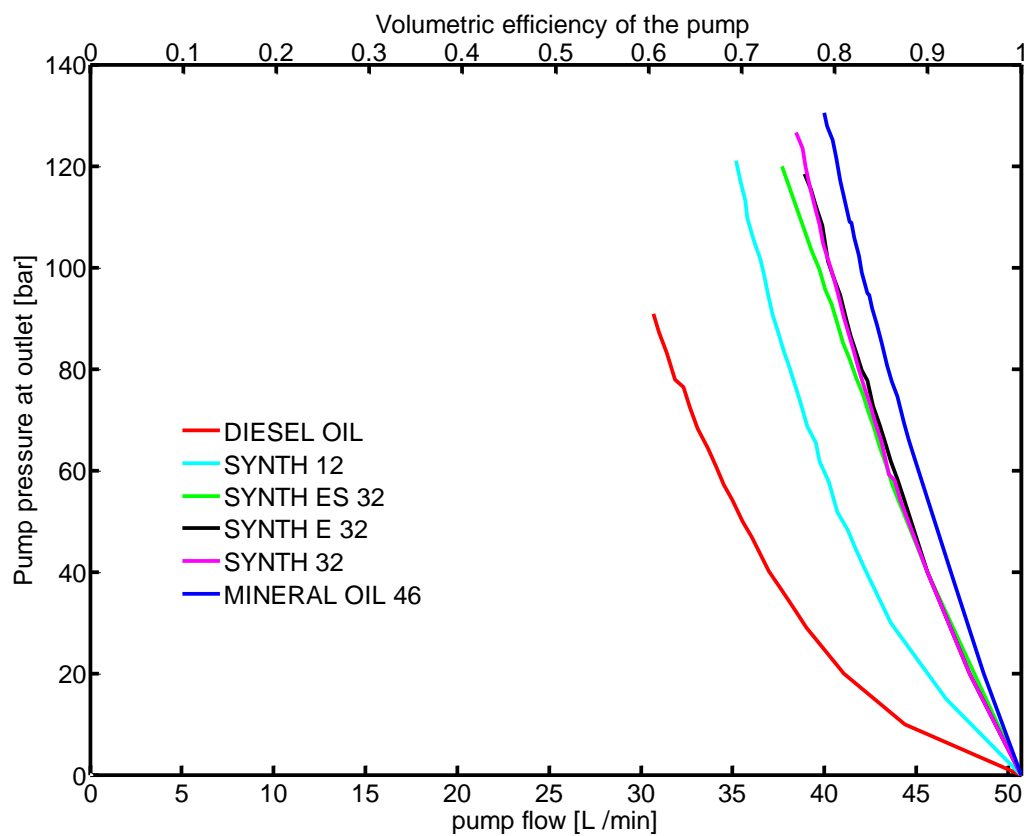


Fig. 5.12. Flow Vs Load on the pump at 40°C

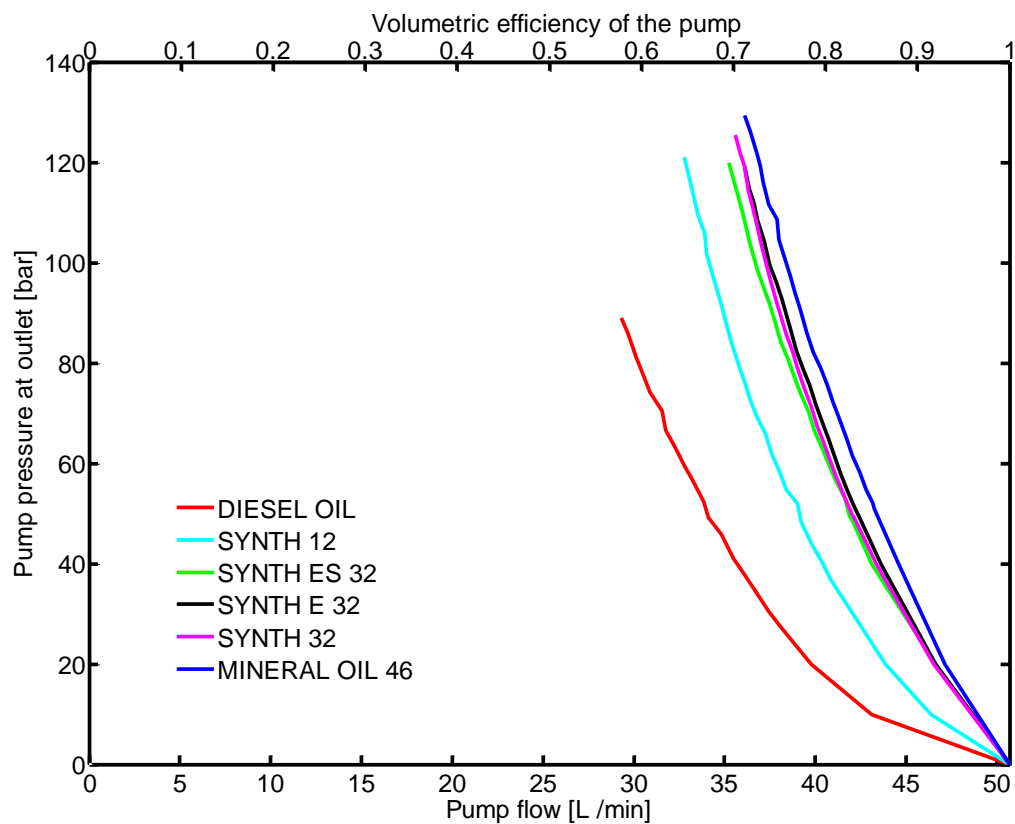


Fig. 5.13. Flow Vs Load on the pump at 50°C

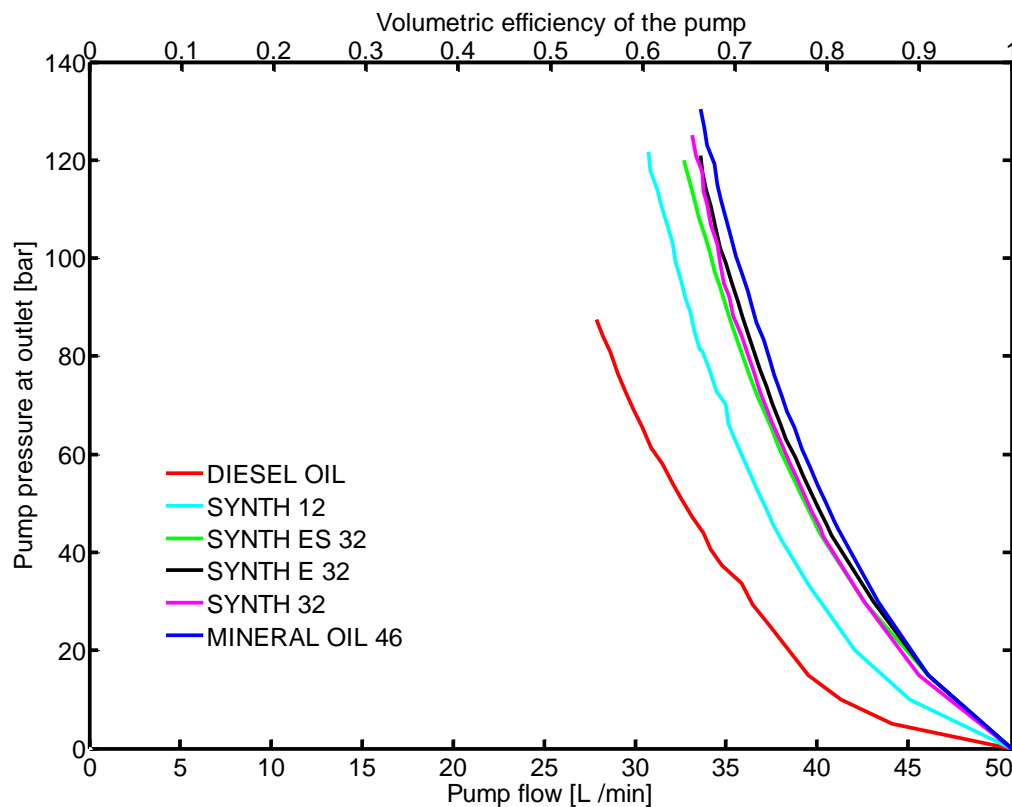


Fig. 5.14. Flow Vs Load on the pump at 60°C

5.5. Comparative performance of all fluids on hose at constant flow

The data collected for the pressure losses in hose by varying flow at four different temperatures are taken and they are cross plotted at constant flow that is to study the pressure losses by varying the temperature of the fluid. Here the flow is **25 L/min**. The purpose of this plot is to study the pressure losses in hose with varying viscosity where viscosity is inversely proportional to temperature. The viscosities that are mentioned across the plots are taken from the **fig.1.3**. From the plot it is noticed that the pressure losses in the hose does not vary much with change in temperature for **synth 12** and **diesel oil** this may be due to high viscosity index for both **synth 12** and **diesel oil** but it is different in other fluids where pressure losses vary much with change in temperature.

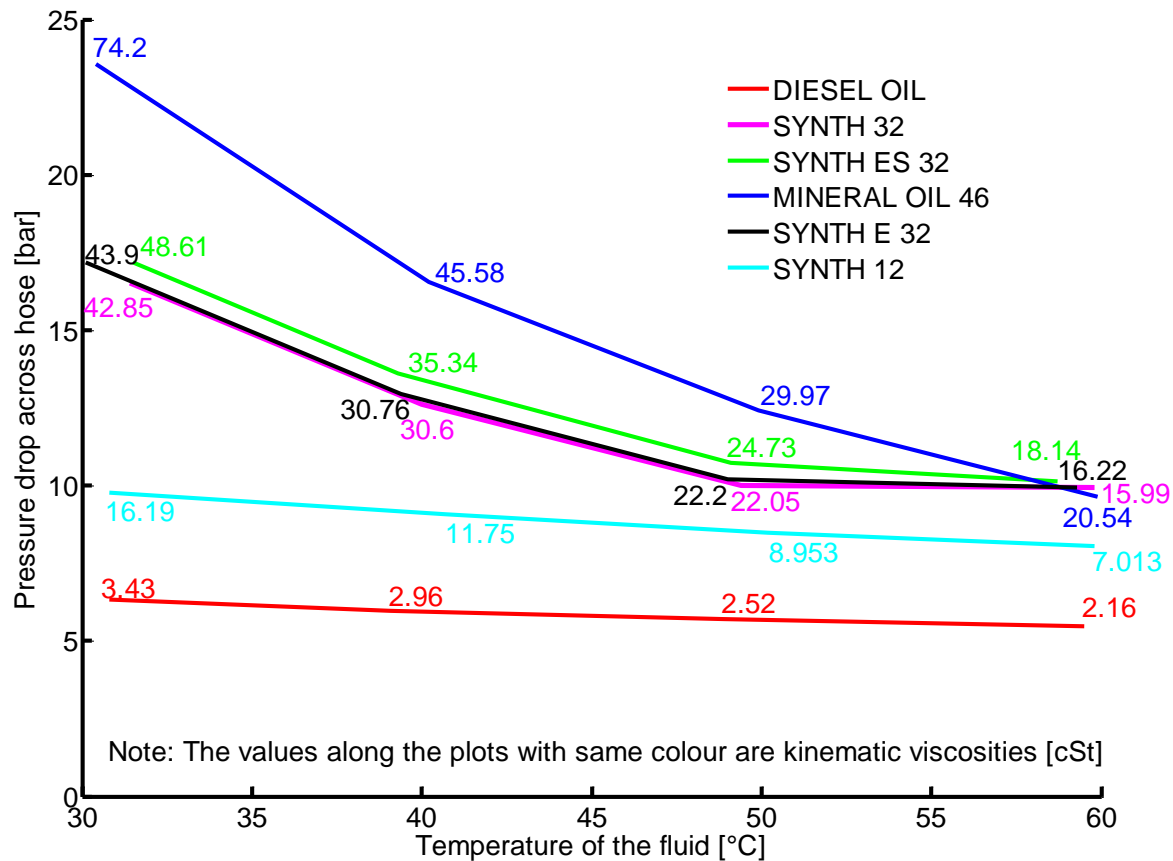


Fig. 5.15. Temperature Vs Pressure drop across hose at constant flow 25 L/min

5.6. Comparative performance of all fluids on pump at constant pump pressure

In this also it is same that the data collected at four temperatures are cross plotted but at constant pump pressure 90 bar. The purpose of the plot is to study the volumetric efficiency of the pump with varying viscosity as the pump efficiency mainly depends on the viscosity as in equation of section 1.5. From the plots it is noticed that the volumetric efficiency of the pump varies with almost constant slope of all the fluids.

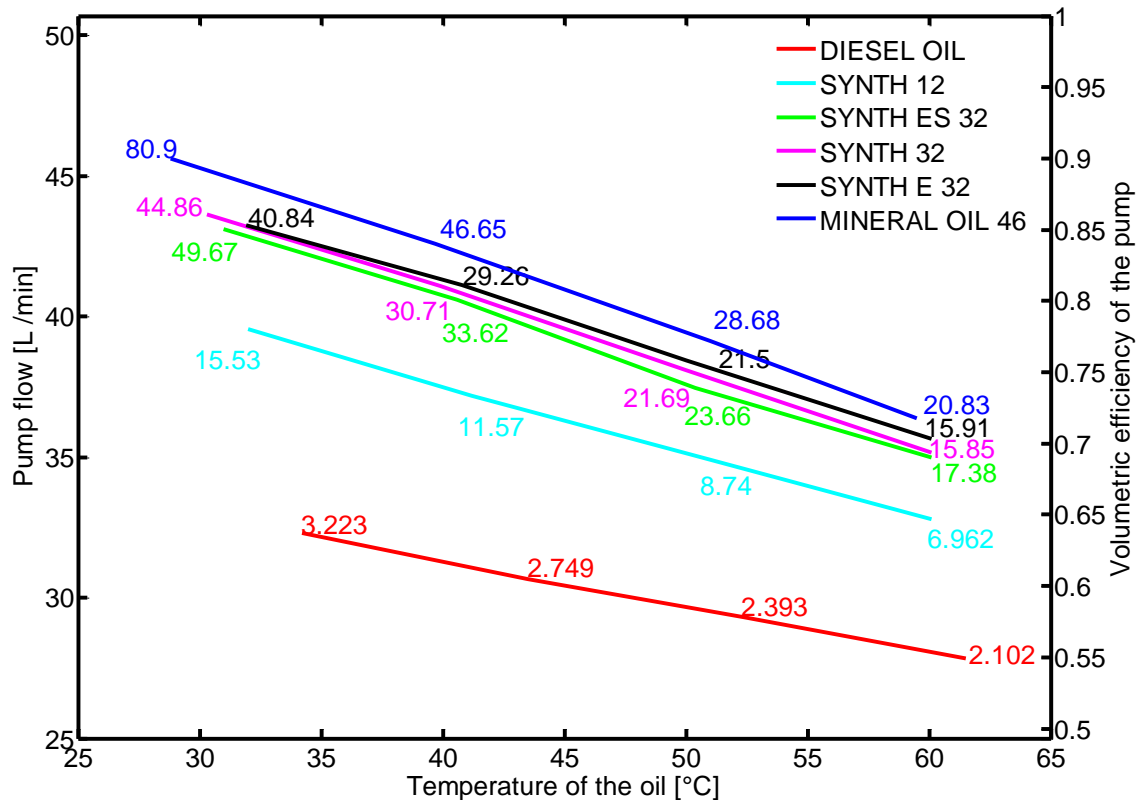


Fig. 5.16. Temperature Vs Pump Flow at constant pressure 90 bar

5.7. Total system efficiency at constant temperature

Total efficiency of the system is calculated based on the data collected according to second test that is in section 5.1.2 by multiplying both volumetric efficiency of the pump and hose efficiency. The volumetric efficiency is calculated by using the formula in section 3.2.1. Here the hose efficiency also includes flow meter, pressure transducers, temperature sensors and other auxiliaries but these are not going to affect the efficiency much. There were no flow losses along the hose. Therefore hose efficiency is based on the formula.

$$\eta_{\text{hose}} = \frac{1}{1 + \frac{\Delta p}{P_2}}$$

where η_{hose} = efficiency of the hose

Δp = pressure drop in hose

P_2 = load pressure

Though this calculation of total efficiency is restricted to this system but this gives some idea to predict the other efficiencies like the mechanical efficiency of the pump. It has been plotted only for the temperatures at 40°C and 50°C because these are the common operating temperatures for most of the systems.

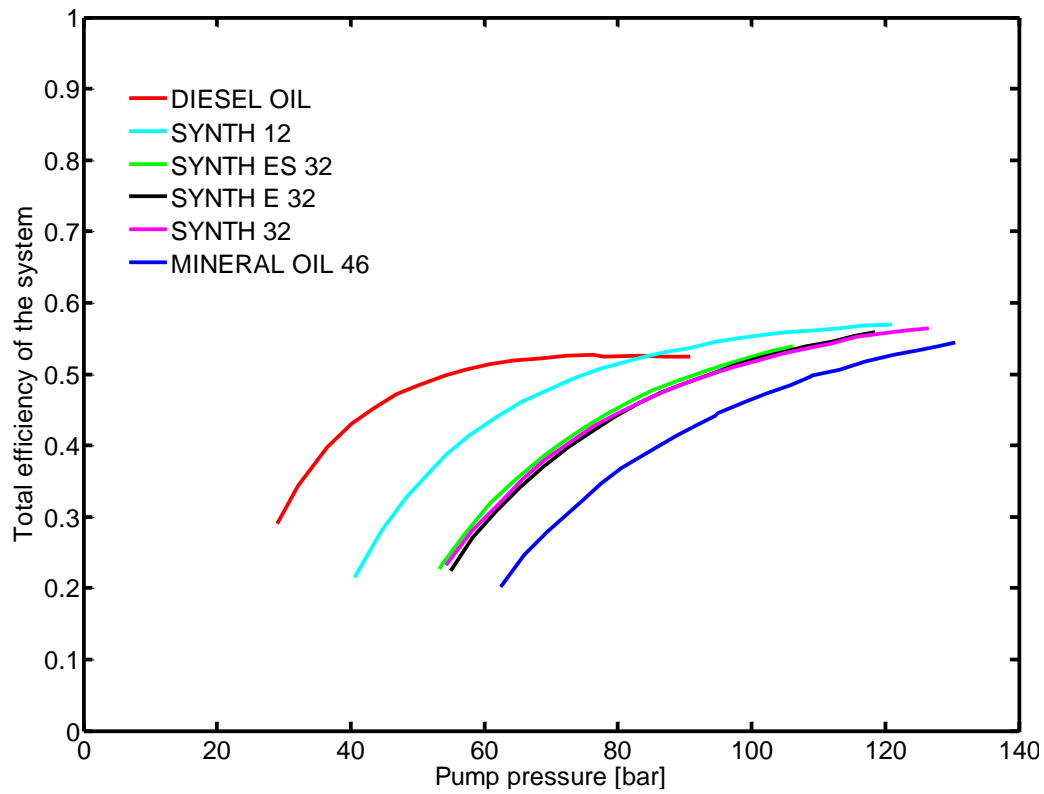


Fig. 5.17. Load Vs total system efficiency at 40°C

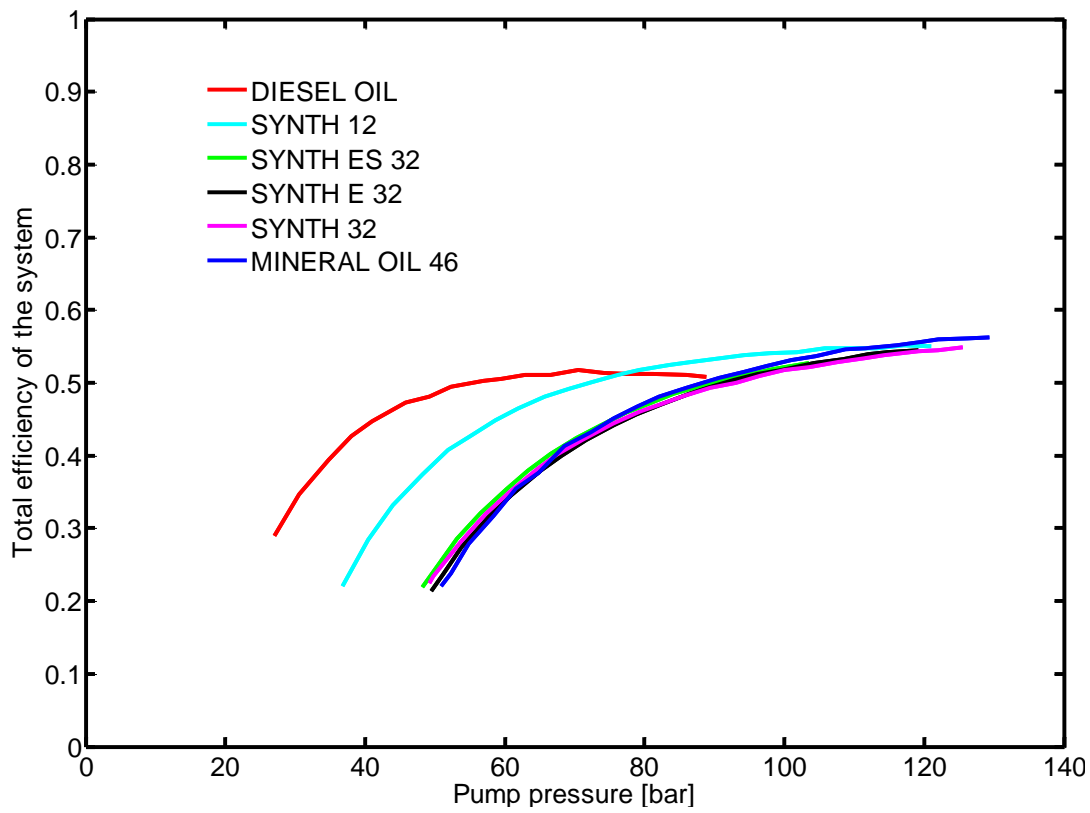


Fig. 5.18. Load Vs total system efficiency at 50°C

From the plots it is noticed that the efficiency of the **diesel oil** is increasing with increase in pump pressure upto 80 bar at 40°C and 70 bar at 50°C and then decreasing. This is due to higher flow losses in pump and constant pressure losses in hose. Since the pump is not designed for the lower viscosities which are below 10 cSt the flow losses are more. But when the mechanical efficiency is considered it could be more for **diesel oil** because viscosity is inversely proportional to mechanical efficiency of the pump and motor and this will directly lead to the increase in total efficiency of the system compared to other fluids. So when the pump or motor that are designed for lower viscosities are used the performance of the fluid will increase.

When other fluids are considered the total efficiency of the **synth 12** becomes constant at 110 bar at 50°C which is equal to all the three **synth 32** and **mineral oil 46**. By this we can say that pressure losses in hose can be compensated with flow losses in pump

5.8. Total system efficiency at constant load

Based on data from the above plots the graph is cross plotted at constant pump pressure 90 bar.

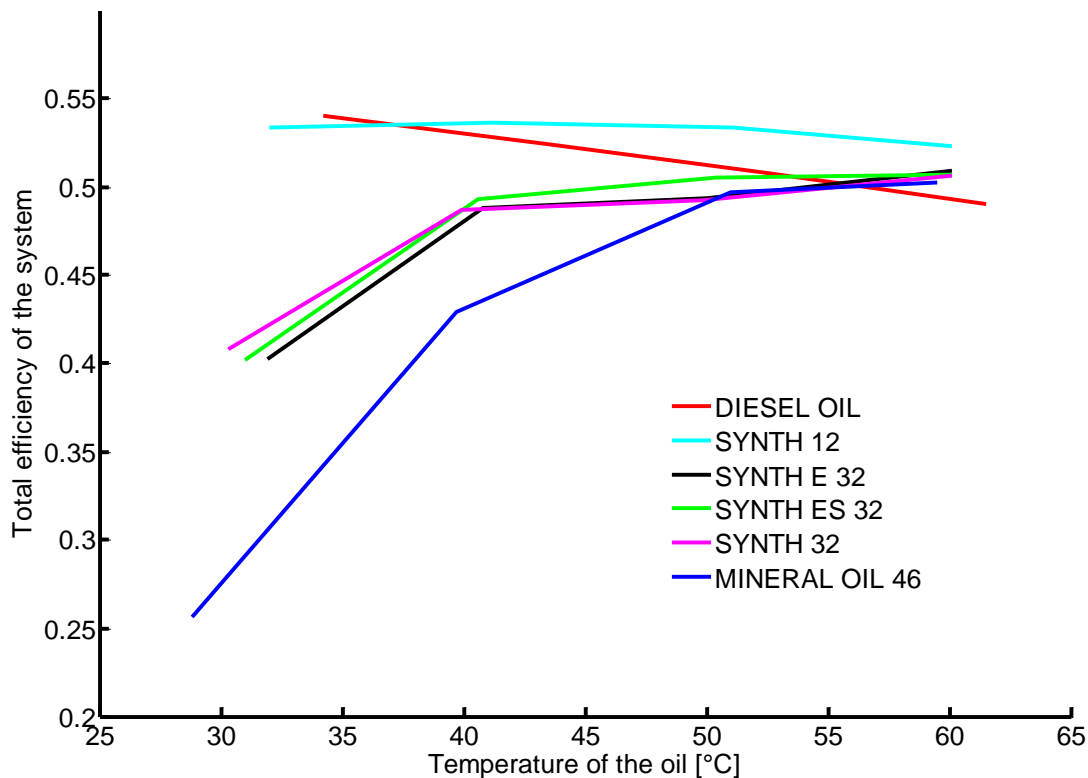


Fig. 5.19. Temperature Vs total system efficiency at 90 bar pump pressure

From the plots it is noticed that the efficiency of the **synth 12** is constant upto 50°C and then it decreases as the temperature increases, where as in **synth 32** fluids and **mineral oil 46** it is in reverse order, the efficiency increases as the temperature increases until 50°C and then it becomes constant. But when **diesel oil** is considered its efficiency decreases as the temperature increases. This is due to higher pump losses as explained above.

5.9. Observations during the test

5.9.1. Air bubbles & other

1. There were no air bubbles in all **synth 32**, **synth e 32**, **synth es 32** and **mineral oil 46** at all the temperatures from 30°C to 60°C. The oil waves in the tank are small.
2. The **mineral oil 46** turns to milky white while running the system at all the temperature.
3. There were very few air bubbles in **synth 12** at all the temperatures, which does not affect the system much. The oil waves in the tank are small.
4. There were foam like air bubbles in **diesel oil** at lower temperatures and it gradually decreasing as the temperature increases and oil waves are very high.

5.9.2. Temperature drop in hose

There is temperature drop of maximum 4°C of all the fluids and at all the temperatures when the temperatures are measured at starting of the hose and in tank. Though this could not give the actual temperature drop in hose but it can be predictable that the temperature does not vary much in hose at room temperatures but the temperature drop in hose can be even more at outside working temperatures when the temperatures are below room temperatures.

6. Conclusion

6.1. Diesel oil

The most challenging task of the thesis is to test this fluid because unlike other fluids its viscosity is very low which is below 2 cSt where there is no method to calculate viscosity index and its low flash point which is 90°C. Because the viscosity of the *diesel oil* does not vary much with temperature it is the best fluid to use in sub zero temperatures. But when higher temperatures are considered more care should be taken because of its low flash point. The fluid is also best suitable for the machines where very long hoses are used like the forest machines because of its very low pressure losses. The efficiency of the system decreases at higher pump pressures because of its very low viscosity but the efficiency can be increased if the pump designed for lower viscosities is used. This fluid is presently in use as a lubricant in mechanical transmissions and it is showing very good results, so it may perform well in hydraulic systems too. The noise of the system is very low when this fluid is used, compared to the standard *mineral oil 46* and all *synth 32* fluids. The temperature of the fluid rises very quickly when compared to the mineral oil 46 where it needs better cooling system.

The most important is that the fluid is synthetic bio diesel and it qualified most of the environmental standards in many countries. So it will be the best fluid for the machines like forest, snow removal and off shore, hydroelectric power projects etc. It is already in use as low carbon emission fuel. Compared to normal diesel the emission has been reduced to more than 90% when this *diesel oil* is used as fuel.

6.2. Synth 12

The viscosity of the *synth 12* does not vary much like *diesel oil* with change in temperature, so it can be used in wide temperature range both at sub zero and positive temperatures. The efficiency of the system also does not vary much with change in pump pressure and it is performing well up to the pressures of 110 bar. This fluid is very good in reducing friction, so the mechanical efficiency of the hydraulic machines could be high. This fluid is specially designed for cold climates so it could be the best for the machines like door hydraulics used in hydropower plants etc. The temperature of the system rises quickly when compared to *mineral oil 46* where it needs better cooling system.

This is also environmental friendly fluid where it is easily biodegradable and it has low toxicity. The noise of the system is also very low when compared to *mineral oil 46*.

6.3. All synth 32 fluids

The performance of all the synth 32 fluids is almost equal. The efficiency of the system is almost equal when compared to the *mineral oil 46* at higher temperatures and it increase with decrease in temperature. The pressure losses in the hose are almost equal compared to *mineral oil 46* during turbulent flow where it needs to be low because of its lower viscosity. When total efficiency of the system is considered it does not vary much as compared to the *mineral oil 46*. The noise of the system is almost equal to that of the *mineral oil 46*. The best

quality is that the temperature of the fluid rises slowly which does not need complicated cooling system.

This fluid is environmental friendly fluid with high bio degradability and low toxicity. It got approved as eco friendly fluid in many countries.

7. Future work

There were only few hydraulic tests performed on all the fluids and there are lot more tests to do to study the performance of the fluid and one of the most important is to find the mechanical efficiency of the pump, then only it is possible to find the total efficiency of the pump where the viscosity of the fluid is directly proportional to volumetric efficiency and inversely proportional to mechanical efficiency of the pump or motor as shown in **fig.2.1**.

These tests are conducted for a short period of time, but it is important to know the performance of the system or at least pump or motor by running it for very long hours. Then it is also possible to study the wear in the pump and motor.

The other important test is to find the noise levels of the hydraulic system in decibels. Though the noise levels are comparable when other fluids are considered but it is important to know individually.

9. References

- ¹ Formula Book for Hydraulics and Pneumatics, Fluid and Mechanical Engineering Systems, Department of Management and Engineering, Linköping University.
- ² http://en.wikipedia.org/wiki/Ubbelohde_viscometer
- ³ <http://www.widman.biz/English/Calculators/VI.html>
- ⁴ http://www.ehow.com/list_6298949_hydraulic-fluid-classifications.html
- ⁵ ISO 6743-4:1999 Lubricants, industrial oils and related products (class L) -- Classification -- Part 4: Family H (Hydraulic systems).
- ⁶ <http://en.wikipedia.org/wiki/Viscosity>
- ⁷ ISO 2909:2002 - Petroleum products -- Calculation of viscosity index from kinematic viscosity.
- ⁸ http://en.wikipedia.org/wiki/Bulk_modulus
- ⁹ ISO 11158:2009 Lubricants, industrial oils and related products (class L) -- Family H (hydraulic systems) -- Specifications for categories HH, HL, HM, HV and HG
- ¹⁰ ISO 12922:1999 Lubricants, industrial oils and related products (class L) -- Family H (Hydraulic systems) -- Specifications for categories HFAE, HFAS, HFB, HFC, HFDR and HFDU.
- ¹¹ ISO 15380:2011 Lubricants, industrial oils and related products (class L) -- Family H (Hydraulic systems) -- Specifications for categories HETG, HEPG, HEES and HEPR.
- ¹² http://www.boschrexroth.com/country_units/america/united_states/sub_websites/brus_brh_i/en/products_ss/09_pumps/a_downloads/re90221_2002-01.pdf
- ¹³ http://www.boschrexroth.com/country_units/america/united_states/sub_websites/brus_brh_m/en/products_mobile_hydraulics/8_fluid_information_/a_downloads/re90221_2010-05.pdf
- ¹⁴ http://books.google.se/books?id=J_AkNuY1wQC&pg=PA377&lpg=PA377&dq=HETG+operating+temperature&source=bl&ots=j0Ax6KCVhu&sig=iChaMQPV7KvTZ46hZepzbTKxxS4&hl=en&sa=X&ei=wo4pT6m0CcyKswbNt7XgAQ&sqi=2&redir_esc=y#v=onepage&q=HETG%20operating%20temperature&f=false
- ¹⁵ <http://hydraulicspneumatics.com/200/TechZone/HydraulicFluids/Article/False/6484/TechZone-HydraulicFluids>
- ¹⁶ http://www.vaxteko.nu/html/sll/slu/ex_arb_vaxtnaringslara/EVN099/EVN099.HTM

¹⁷ Synthetic lubricants and high-performance functional fluids, second edition, revised and expanded; Andrew G. Papay, Ethyl Petroleum Additives, Inc., St. Louis, Missouri; Leslie R. Rudnick, Infineum USA, L.P., Linden, New Jersey.

¹⁸ BIO-BASED LUBRICANTS, A Market Opportunity Study Update, Prepared for the United Soybean Board, November 2008, By: Bart J. Bremmer & Dr. Larry Plonsker

¹⁹ A NOTE ON THE USE OF THE CEC L-33-A-93 TEST TO PREDICT THE POTENTIAL BIODEGRADATION OF MINERAL OIL BASED LUBRICANTS IN SOIL; N.S. Battersby and P. Morgan.

²⁰ Biobased hydraulic fluid evaluation; Linwood Gilman, DSRC; George Handy, NDCEE/CTC.

²¹ FLUID VISCOSITY SELECTION CRITERIA FOR HYDRAULIC PUMPS AND MOTORS; Steven N. Herzog, RohMax USA, Inc., Horsham, PA; Thelma E. Marougy, Eaton Corporation, Southfield, MI; Paul W. Michael, Benz Oil, Milwaukee, WI.

²² ISO 3104:1994 Petroleum products -- Transparent and opaque liquids -- Determination of kinematic viscosity and calculation of dynamic viscosity.

²³ http://en.wikipedia.org/wiki/Total_Acid_Number

²⁴ http://en.wikipedia.org/wiki/Cleveland_open_cup_method

²⁵ http://en.wikipedia.org/wiki/Pour_point

²⁶ <http://www.spectro-oil.com/tests/2/2/water-by-karl-fischer/>

²⁷ ISO 9120:1997 Petroleum and related products -- Determination of air-release properties of steam turbine and other oils -- Impinger method.

²⁸ <http://www.astm.org/Standards/D2532.htm>

²⁹ <http://www.spectro-oil.com/tests/2/2/elemental-analysis-icp-spectrometry/>

³⁰ ISO 4409-2007 Hydraulic fluid power -- Positive-displacement pumps, motors and integral transmissions -- Methods of testing and presenting basic steady state performance.

³¹ ISO 4411:2008 Hydraulic fluid power -- Valves -- Determination of pressure differential/flow characteristics.

³² http://www.jiskoot.com/Calculations/Density_VCF/index.html

10. Appendix

10.1. Individual fluid test results

The plots shows the comparative performance of the fluids at four different temperatures of first two types of tests. The Reynolds number for each point is calculated for hose using the formula in section 4.2.6 . It is clearly noticeable that pressure losses in turbulent flow is more than the laminar flow.

10.1.1. Diesel oil

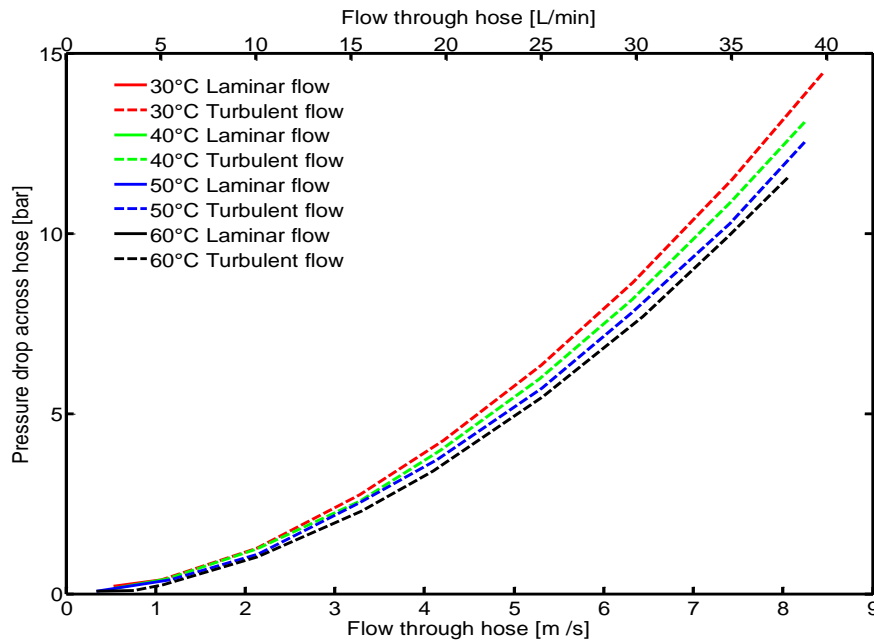


Fig. 10.1. Flow Vs Pressure drop across hose of diesel oil

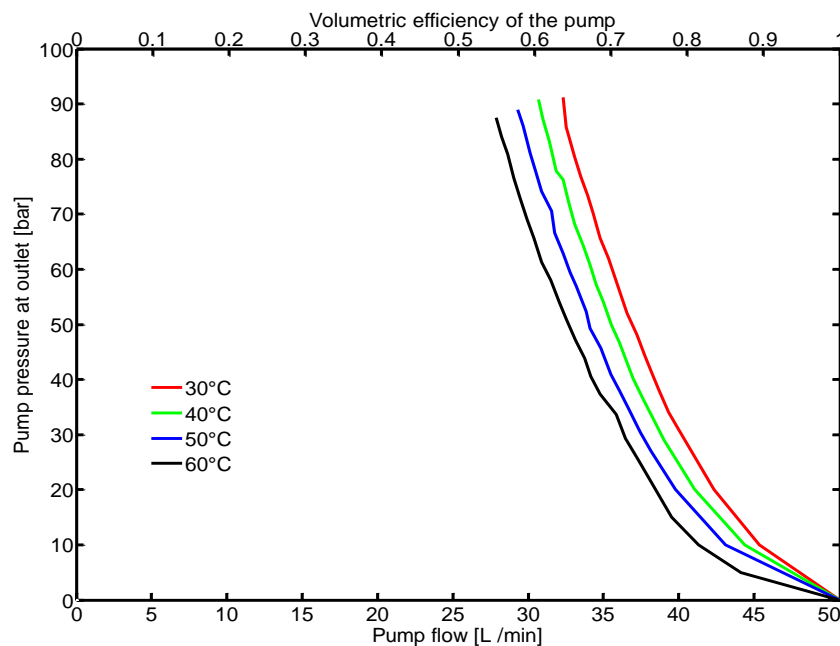


Fig.10.2. Flow Vs Load on the pump of diesel oil

10.1.2. Synth 32

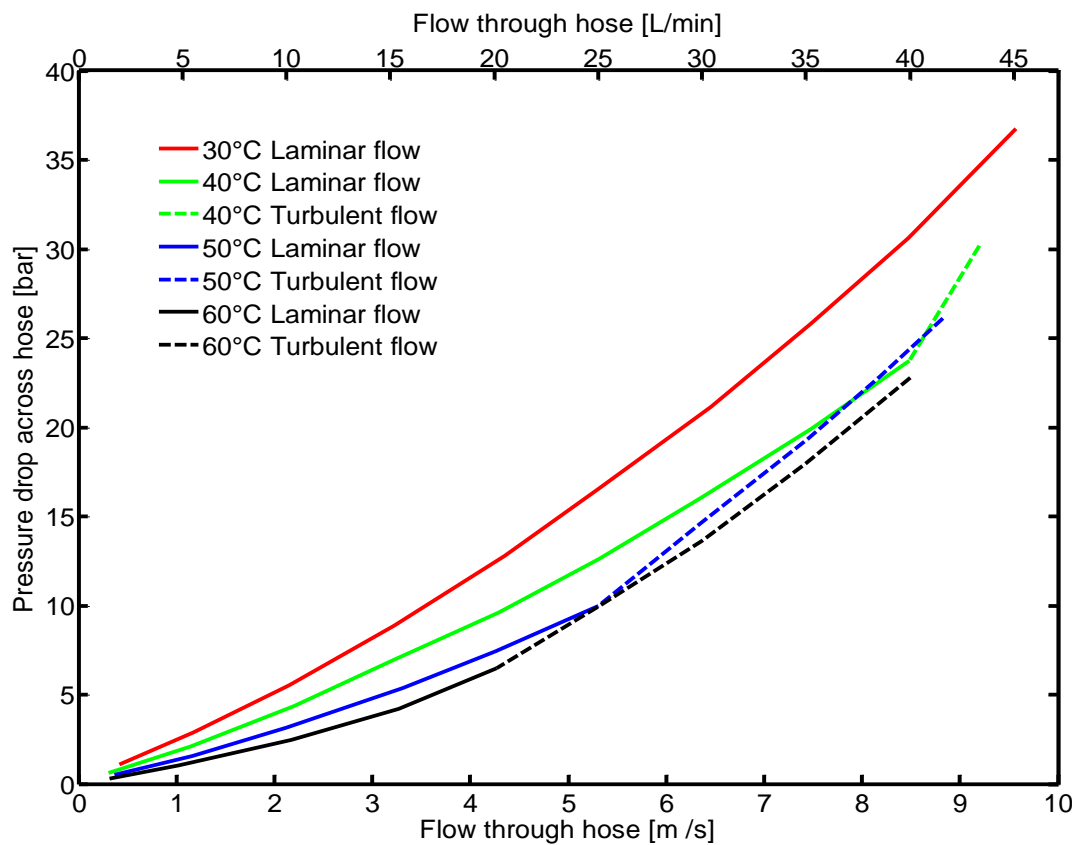


Fig. 10.3. Flow Vs Pressure drop across hose of synth 32

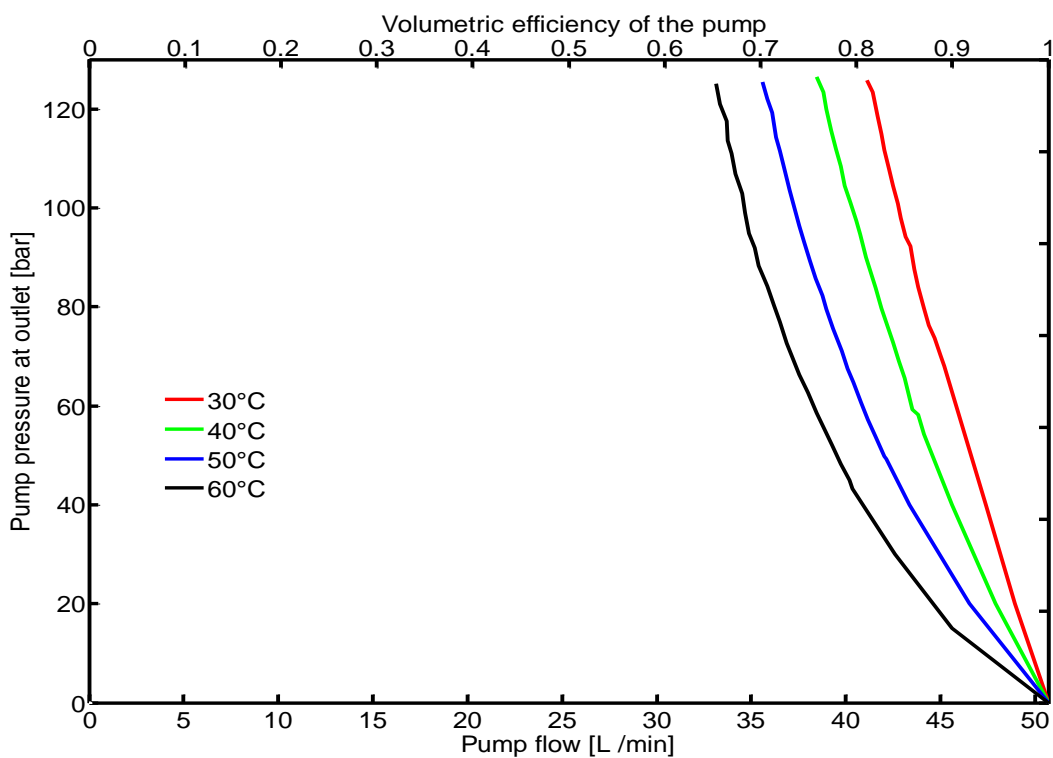


Fig.10.4. Flow Vs Load on the pump of synth 32

10.1.3. Synth e 32

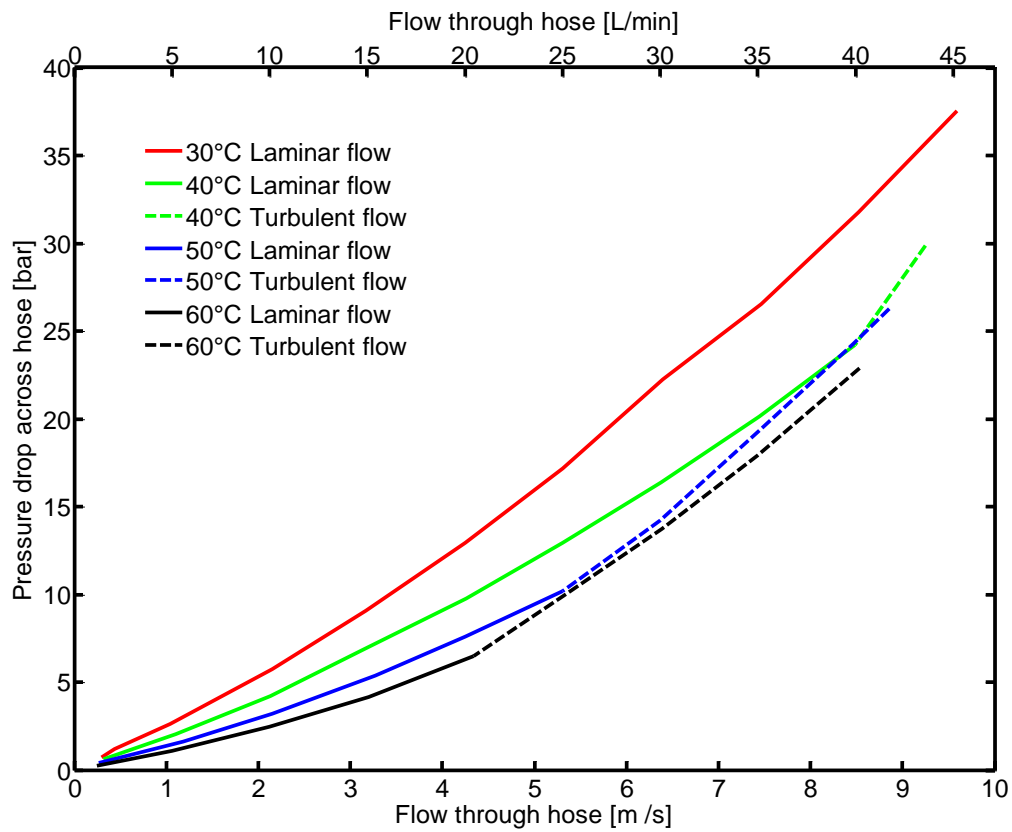


Fig. 10.5. Flow Vs Pressure drop across hose of synth e 32

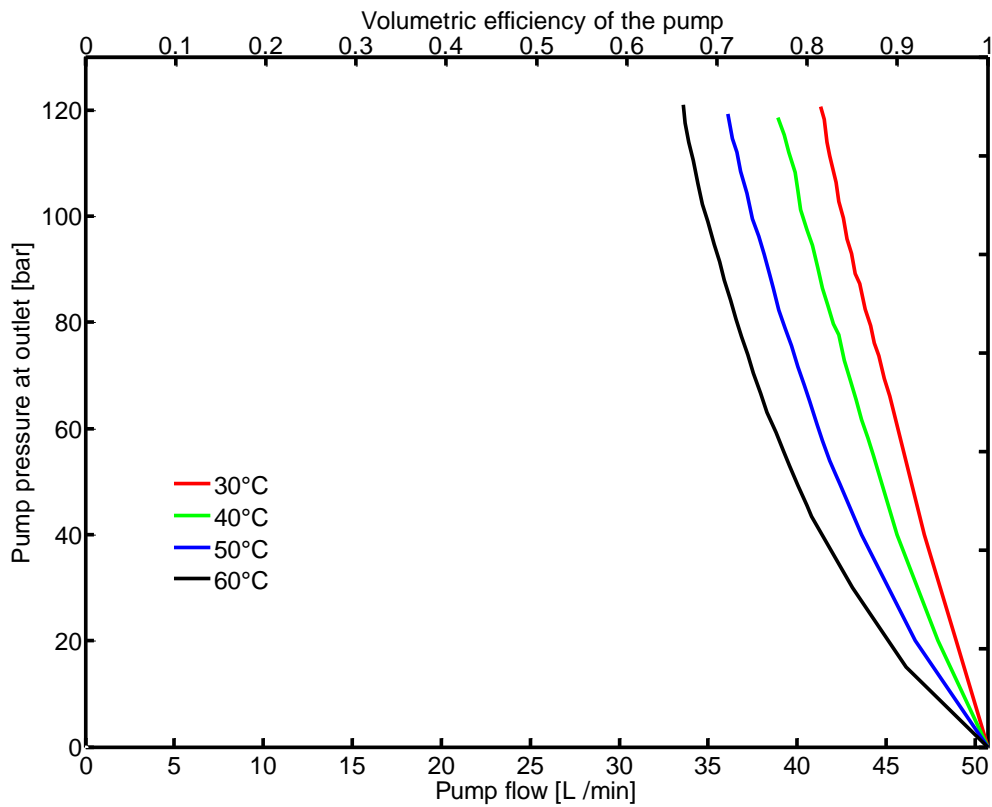


Fig.10.6. Flow Vs Load on the pump of synth e 32

10.1.4. Synthesis 32

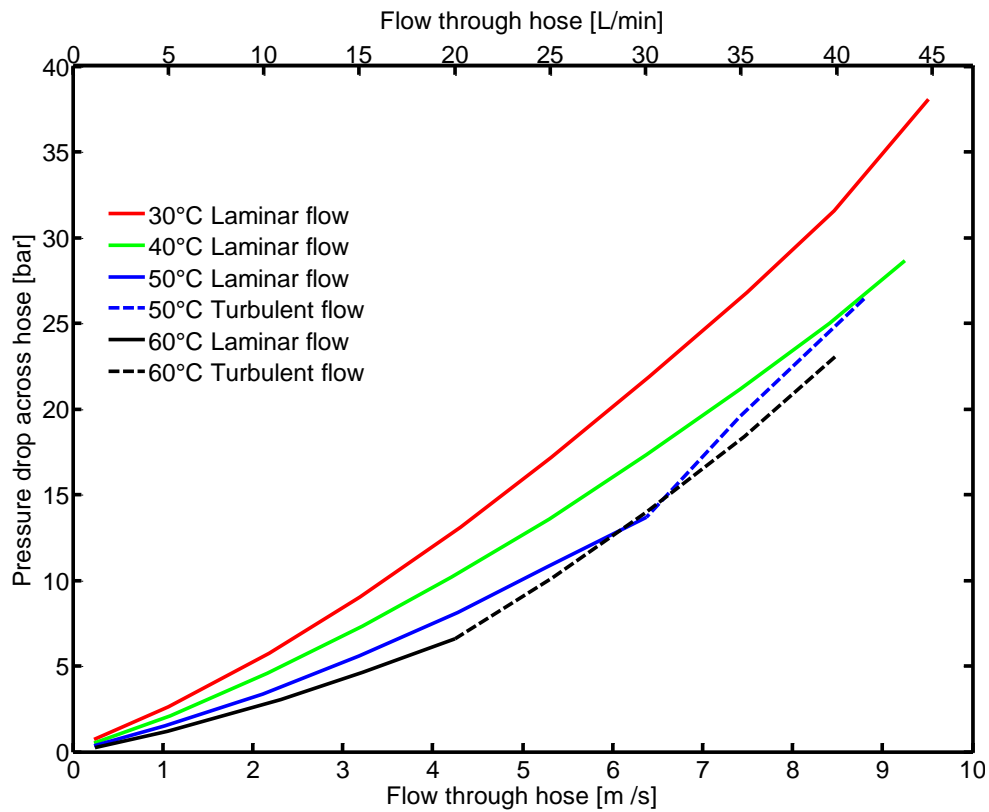


Fig. 10.7. Flow Vs Pressure drop across hose of synthesis 32

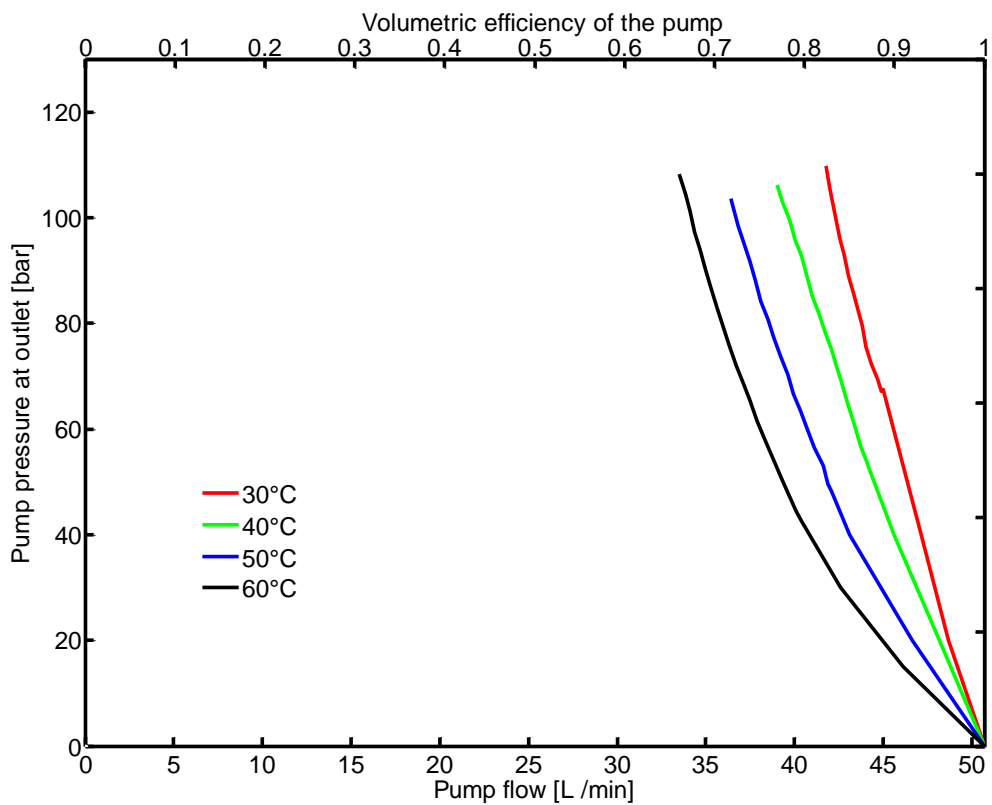


Fig. 10.8. Flow Vs Load on the pump of synthesis 32

10.1.5. Synth 12

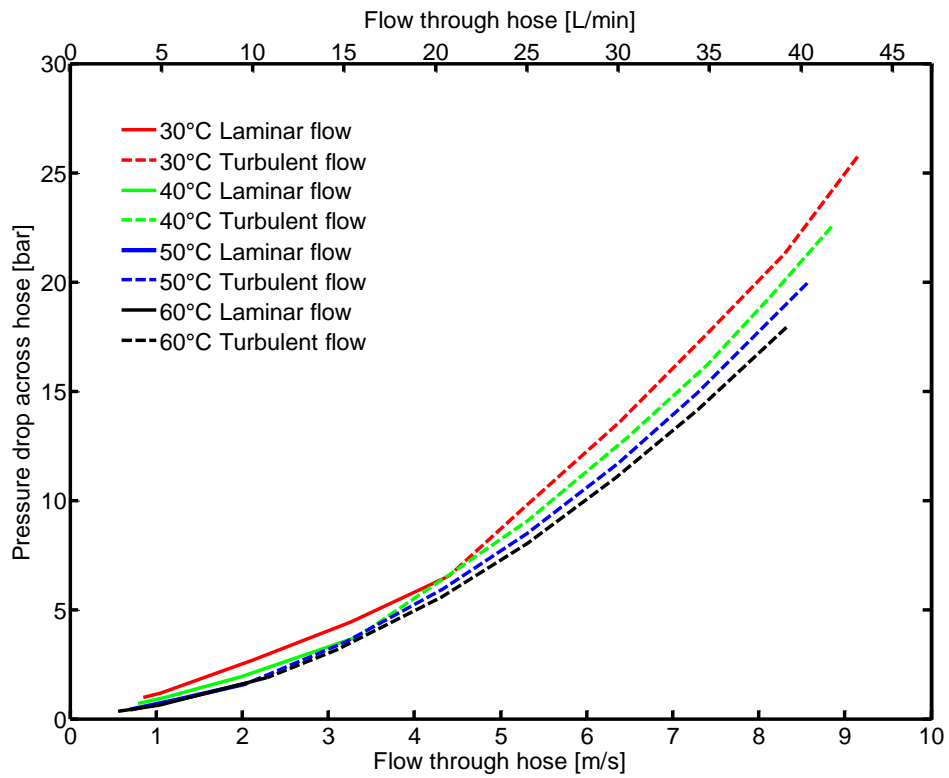


Fig. 10.9. Flow Vs Pressure drop across hose of synth 12

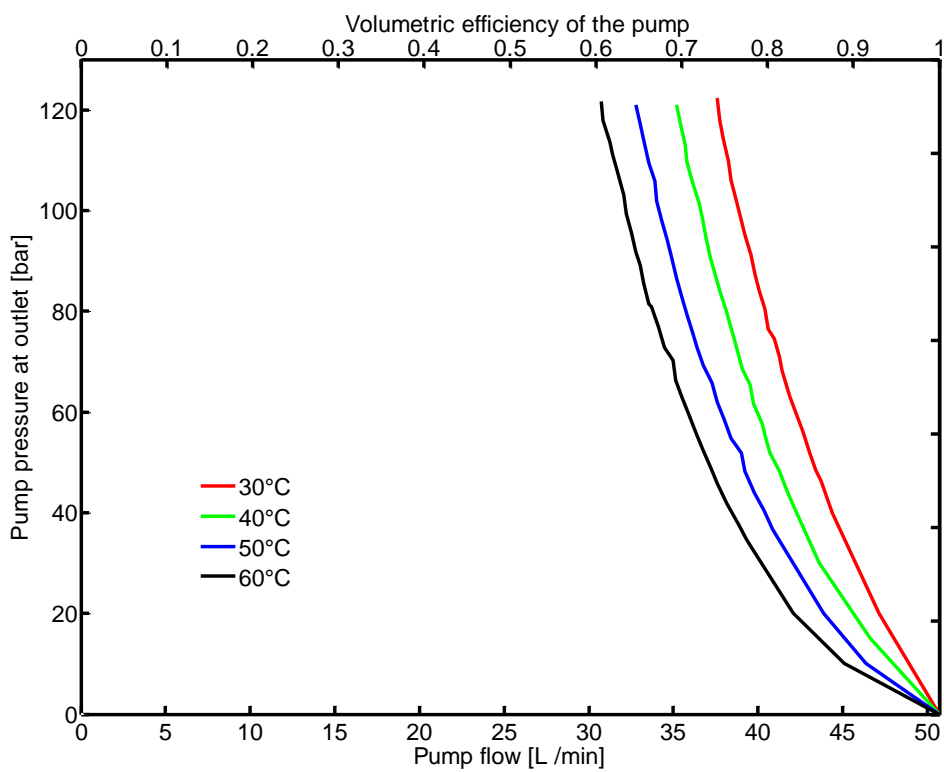


Fig. 10.10. Flow Vs Load on the pump of synth 12

10.1.6. Mineral oil 46

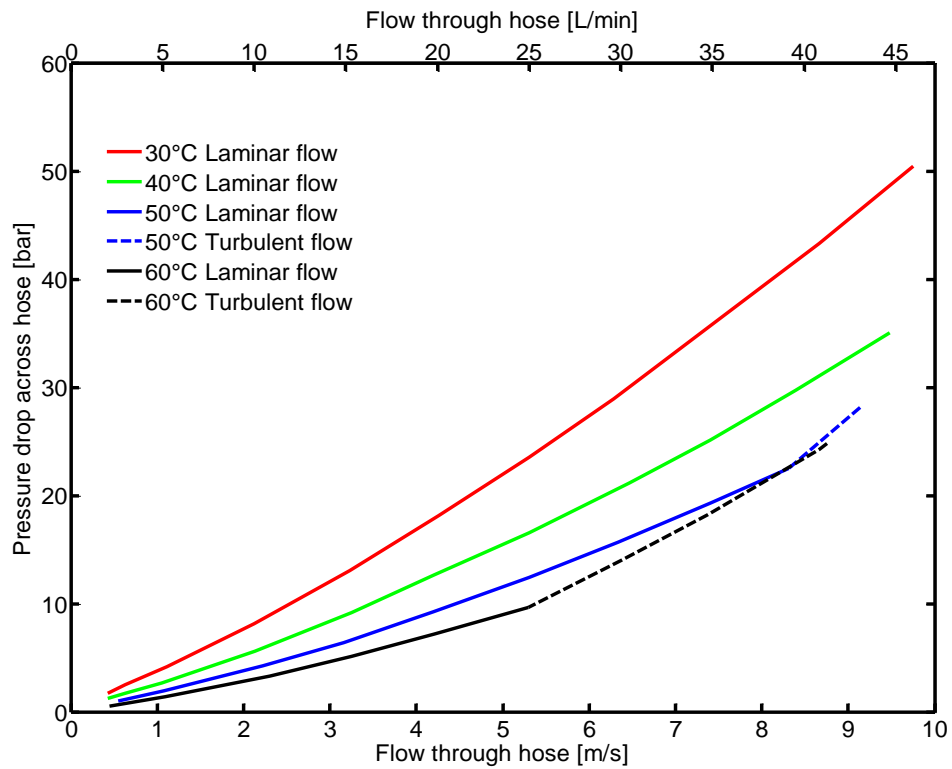


Fig. 10.11. Flow Vs Pressure drop across hose of mineral oil 46

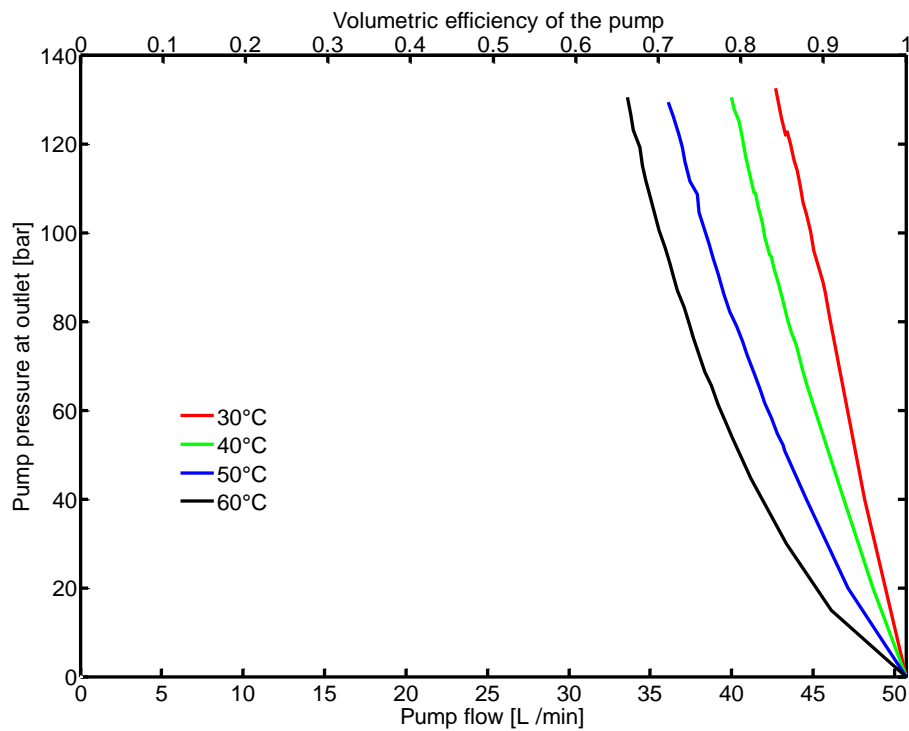


Fig. 10.12. Flow Vs Load on the pump of mineral oil 46

10.2. Comparing with simulation results

10.2.1. Diesel oil

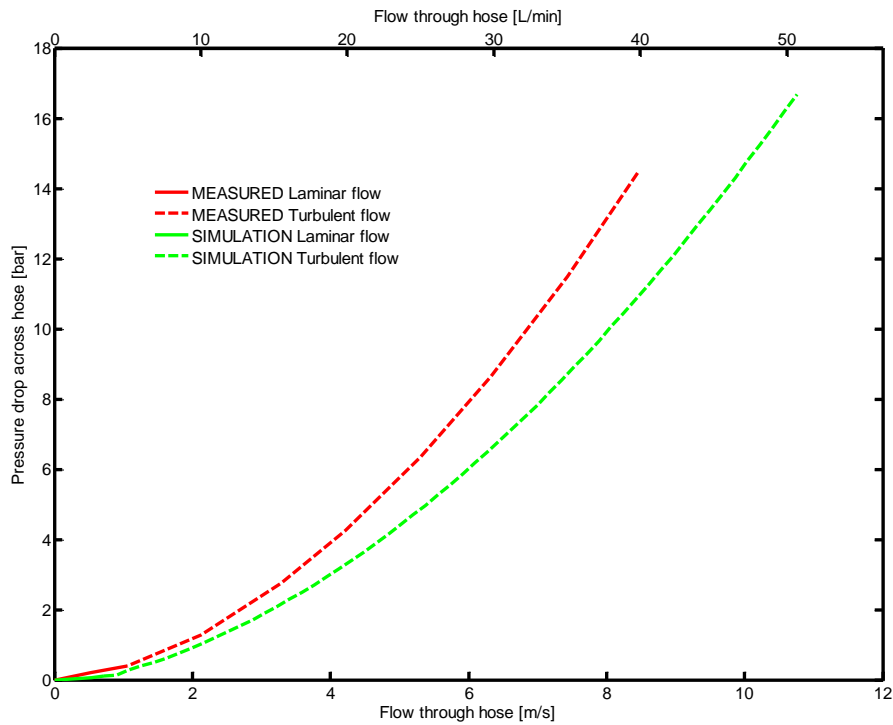


Fig. 10.13. Flow Vs Pressure drop across hose of diesel oil at 30°C

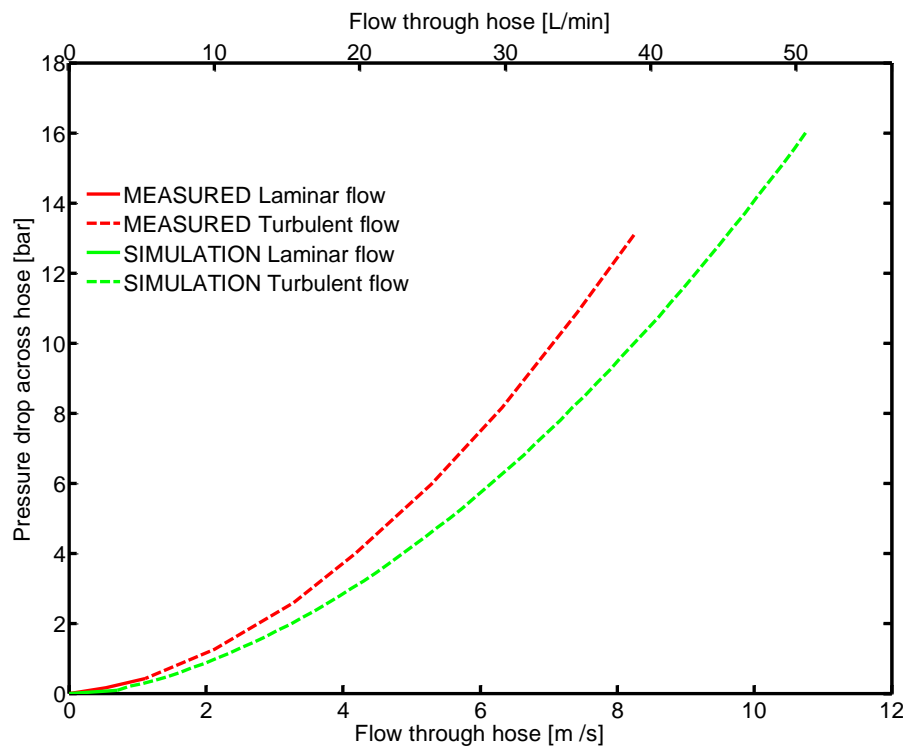


Fig. 10.14. Flow Vs Pressure drop across hose of diesel oil at 40°C

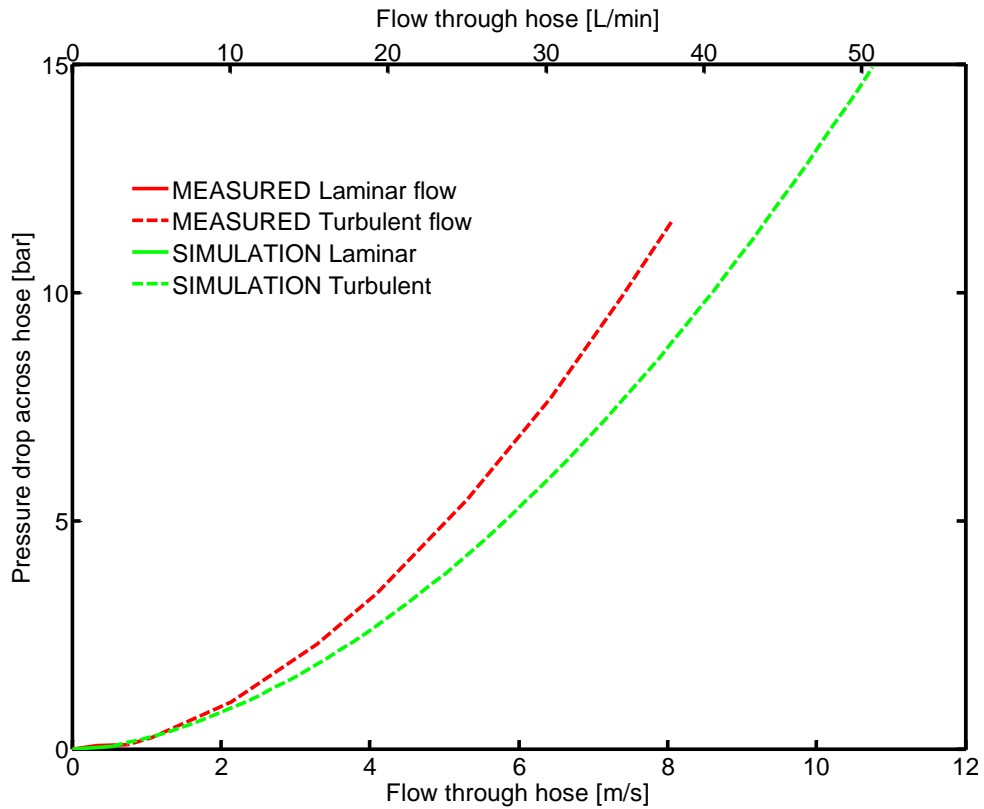


Fig. 10.15. Flow Vs Pressure drop across hose of diesel oil at 60°C

10.2.2. Synth 12

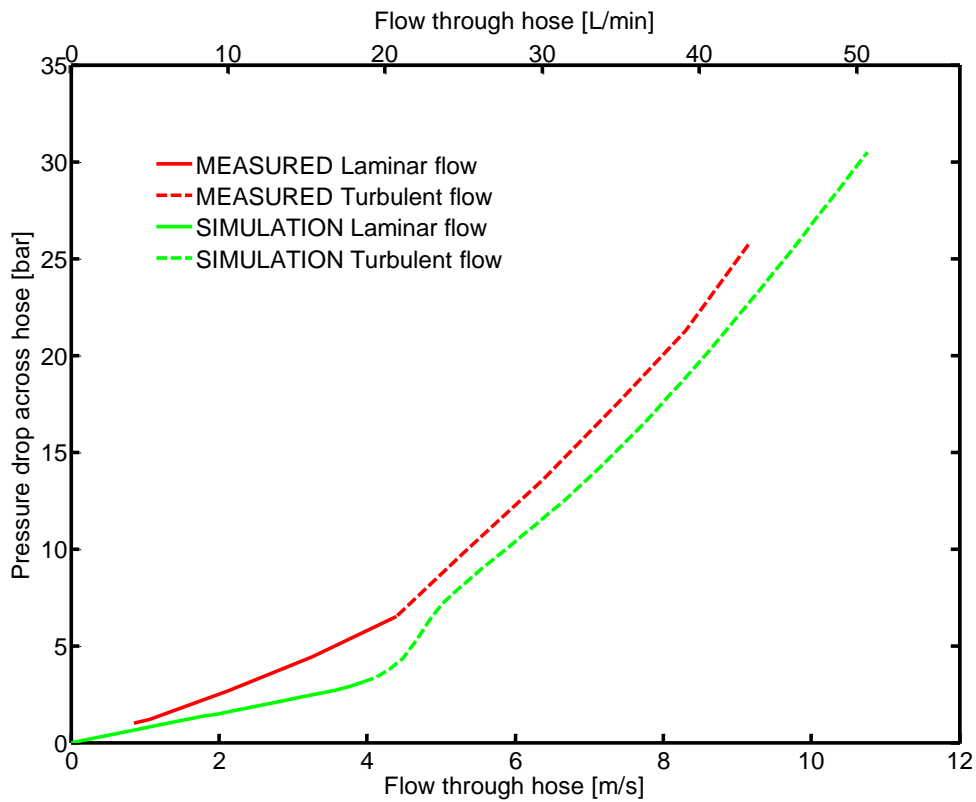


Fig. 10.16. Flow Vs Pressure drop across hose of synth 12 at 30°C

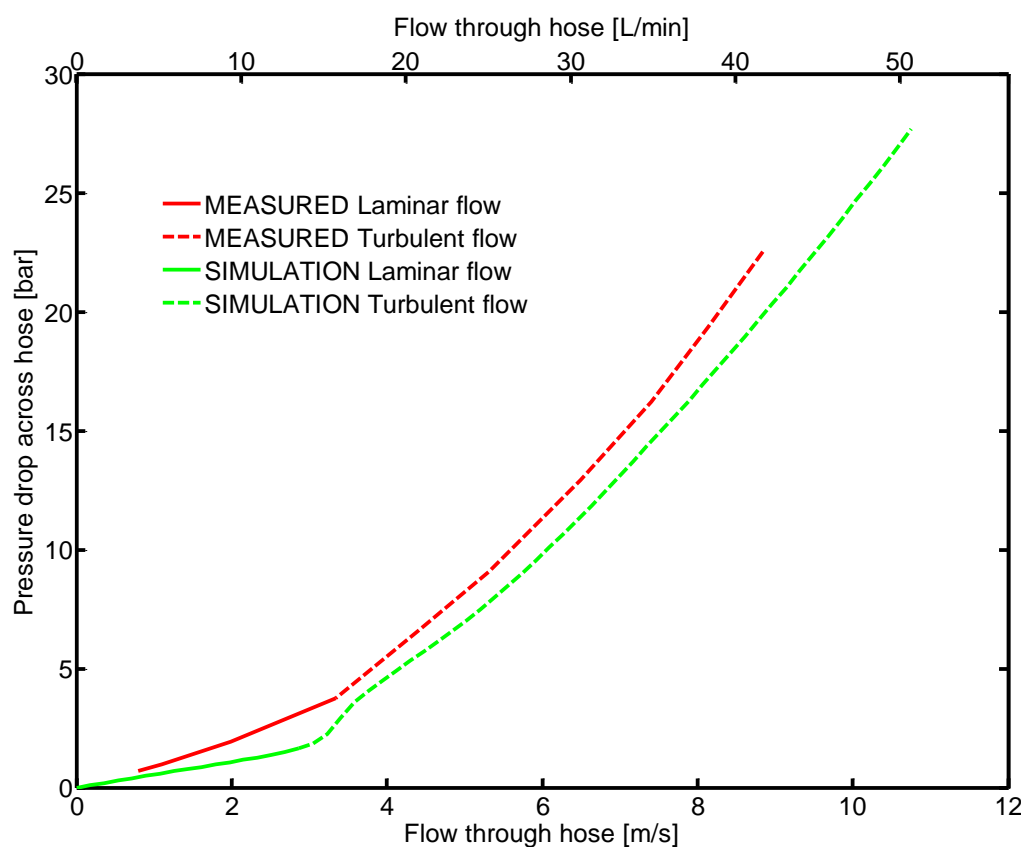


Fig. 10.17. Flow Vs Pressure drop across hose of synth 12 at 40°C

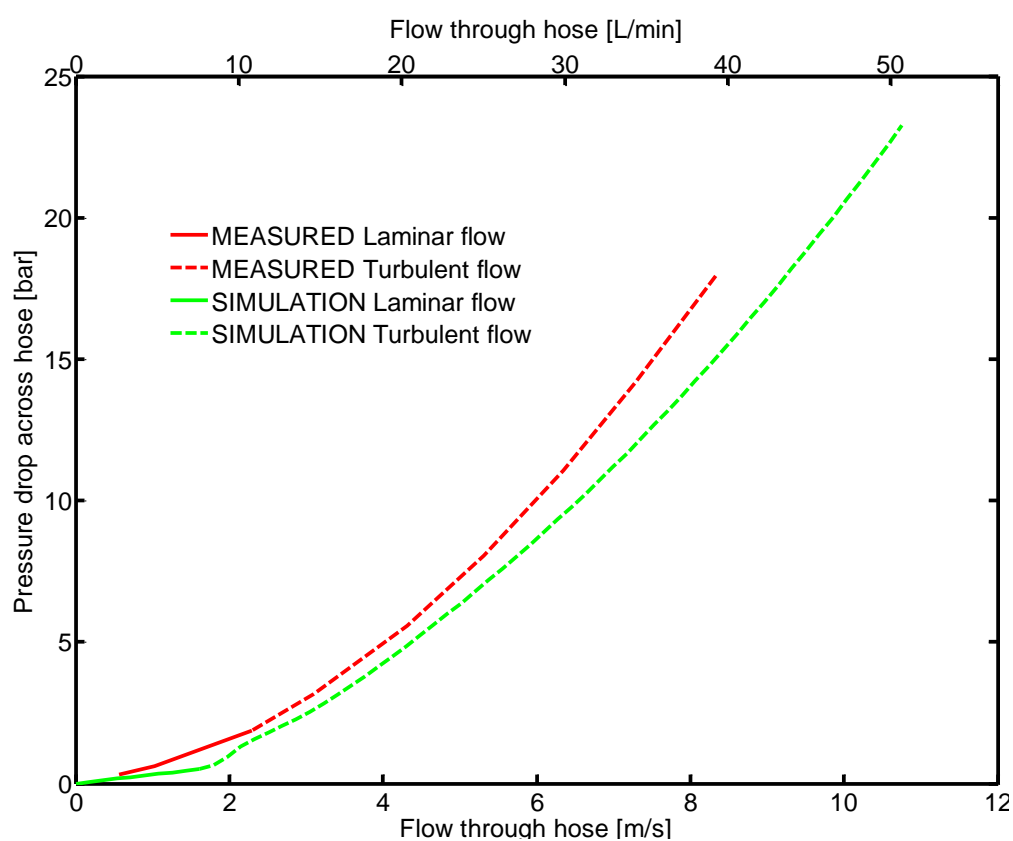


Fig. 10.18. Flow Vs Pressure drop across hose of synth 12 at 60°C

10.2.3. Synth 32

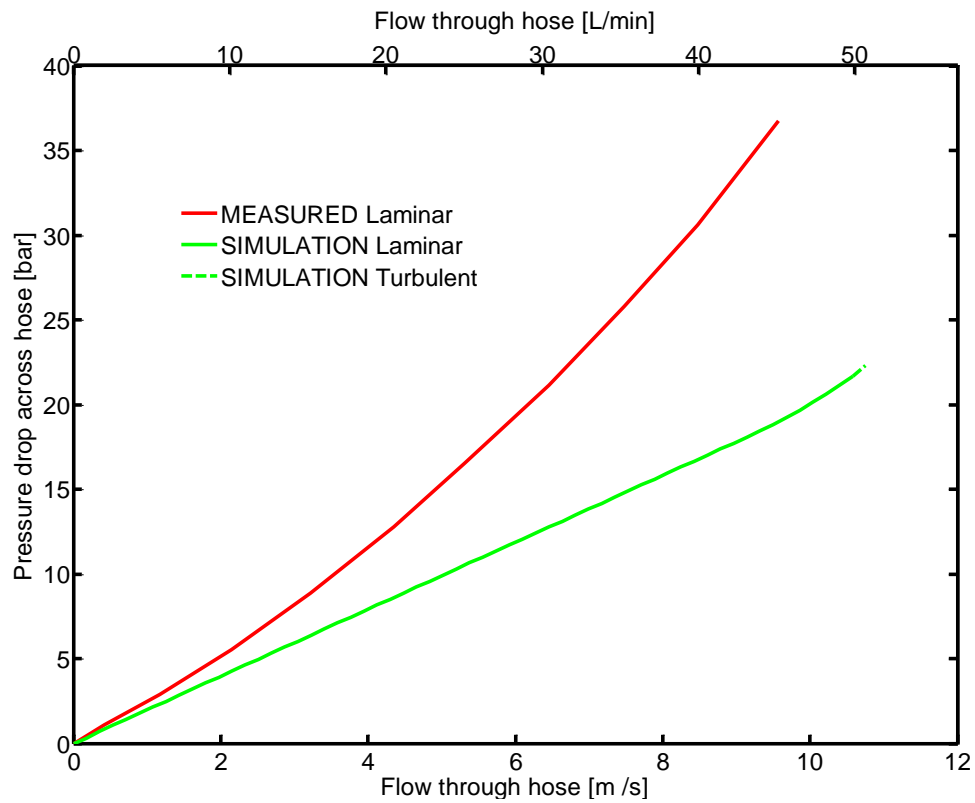


Fig. 10.19. Flow Vs Pressure drop across hose of synth 32 at 30°C

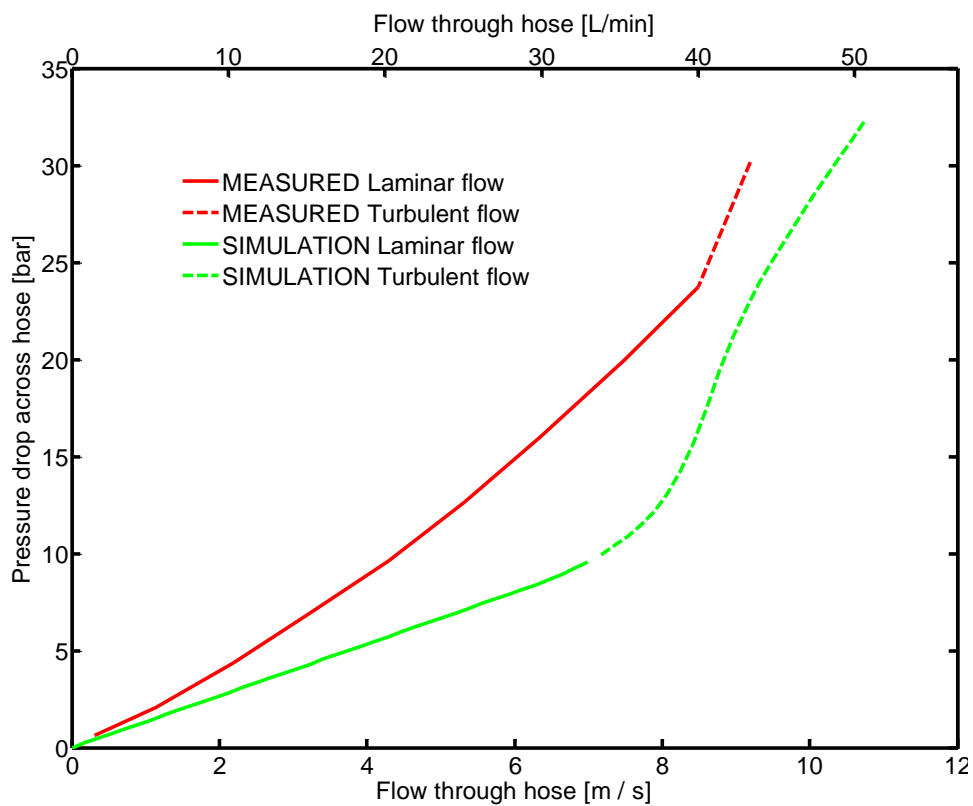


Fig. 10.20. Flow Vs Pressure drop across hose of synth 32 at 40°C

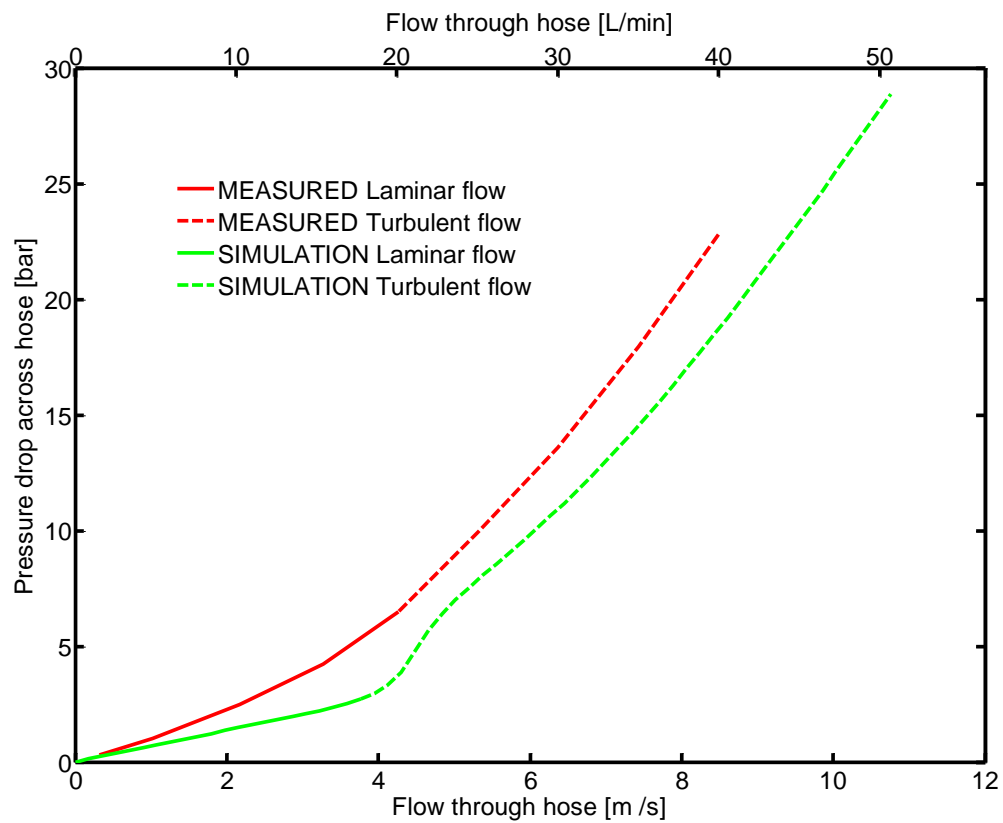


Fig. 10.21. Flow Vs Pressure drop across hose of synth 32 at 60°C

10.2.4. Synth e 32

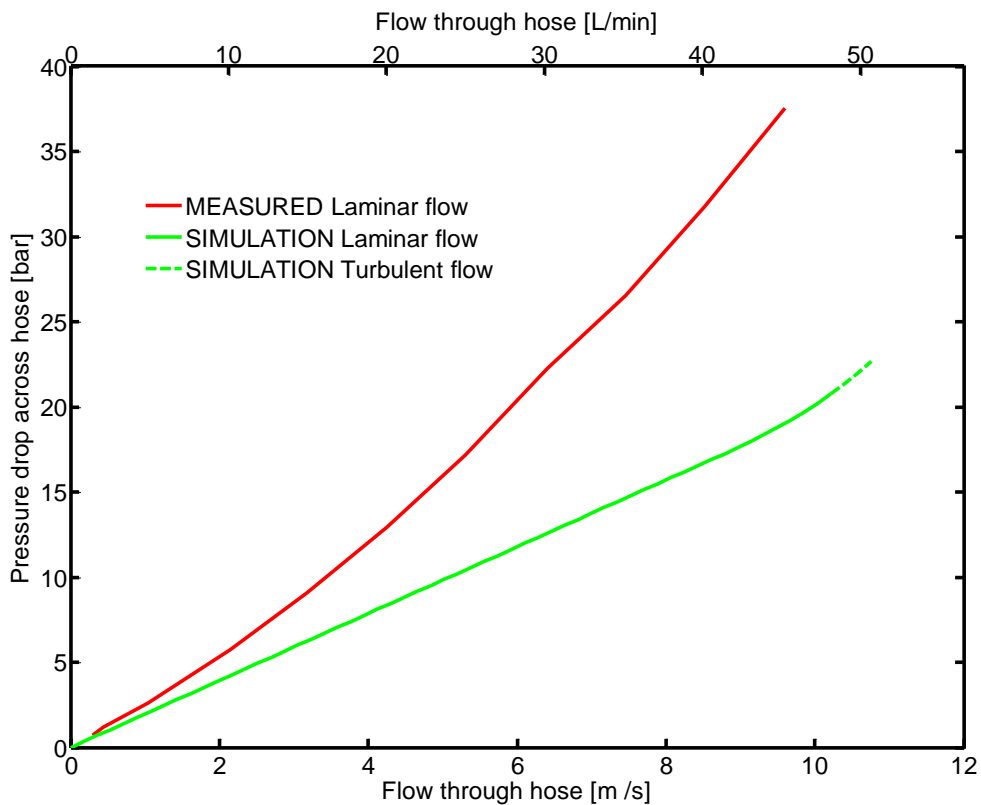


Fig. 10.22. Flow Vs Pressure drop across hose of synth e 32 at 30°C

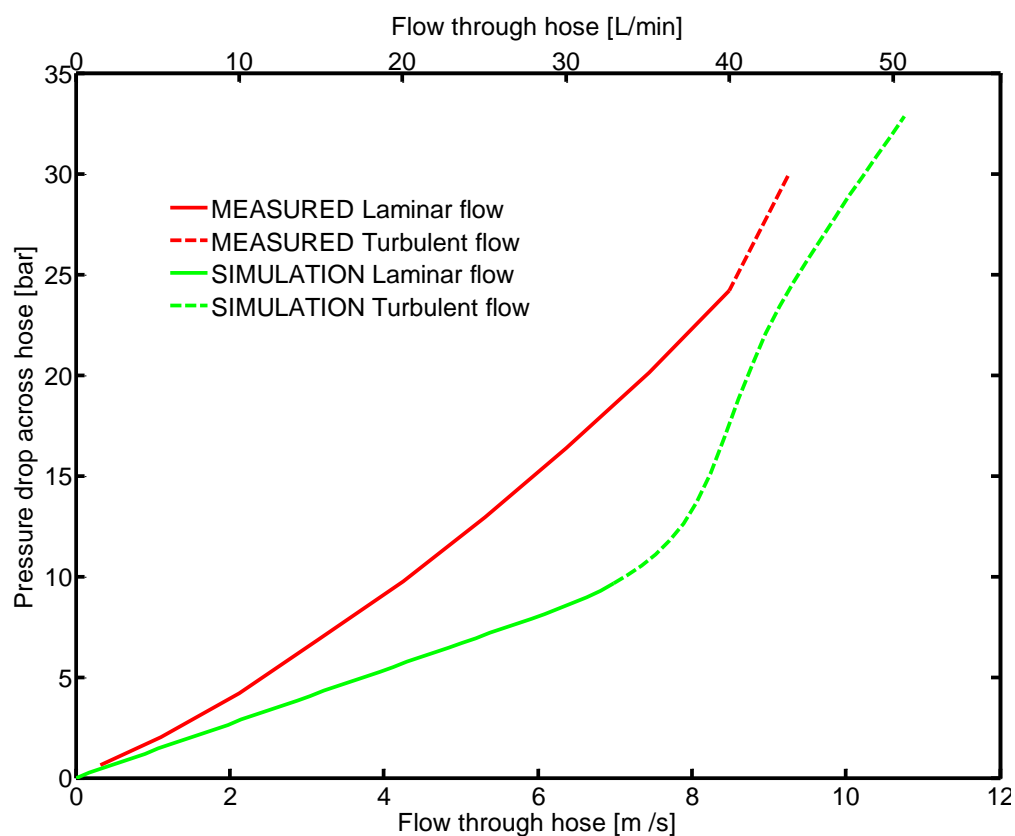


Fig. 10.23. Flow Vs Pressure drop across hose of synth e 32 at 40°C

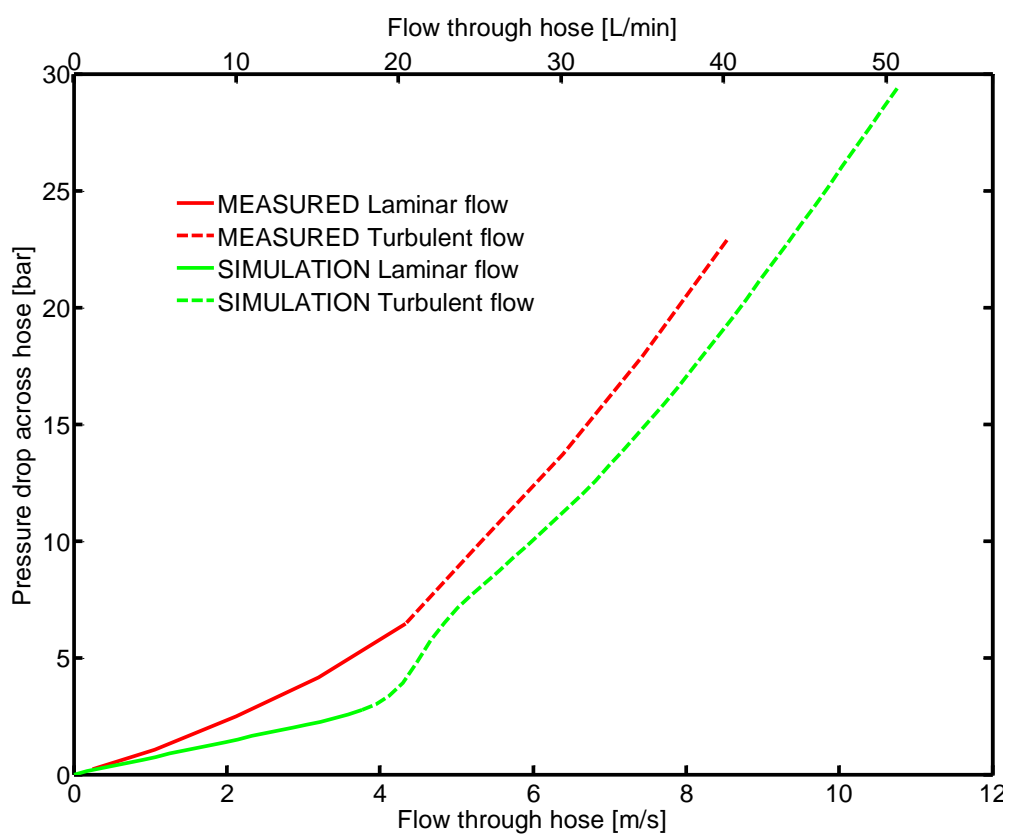


Fig. 10.24. Flow Vs Pressure drop across hose of synth e 32 at 60°C

10.2.5. Synthesis 32

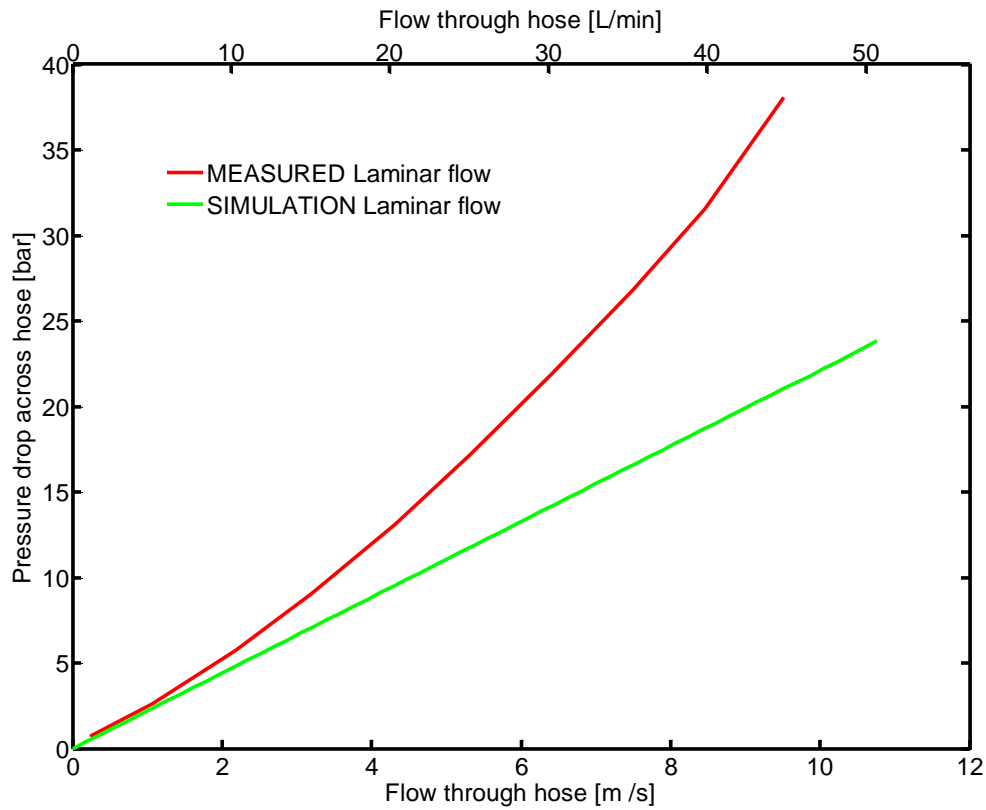


Fig. 10.25. Flow Vs Pressure drop across hose of synthesis 32 at 30°C

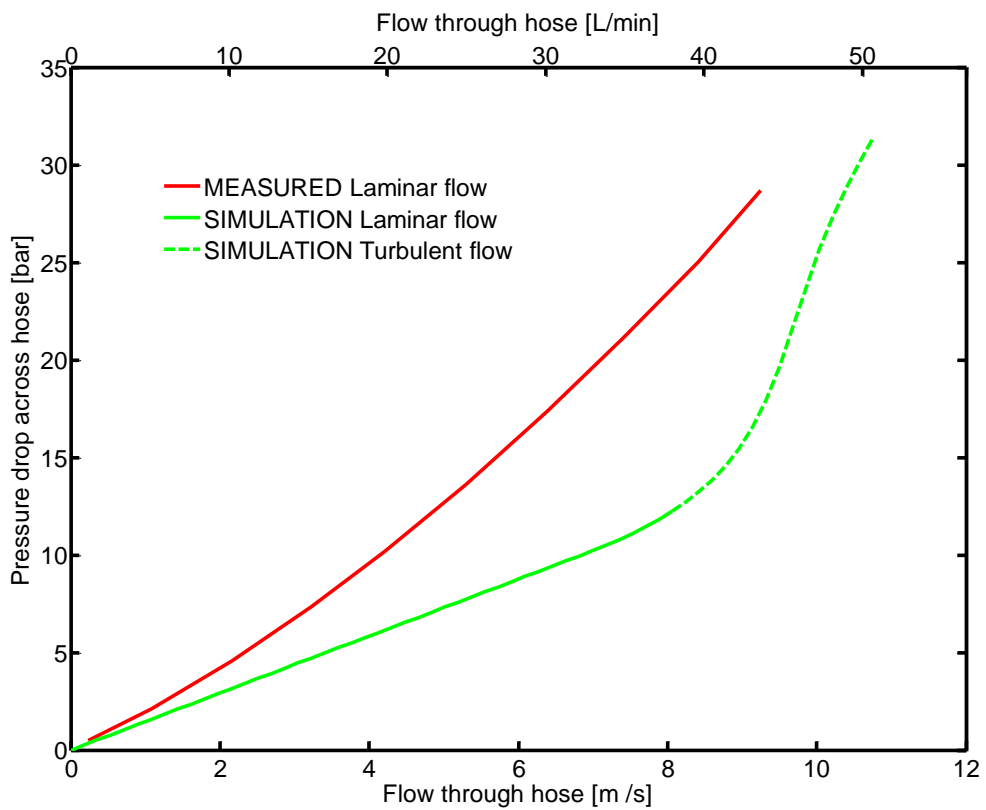


Fig. 10.26. Flow Vs Pressure drop across hose of synthesis 32 at 40°C

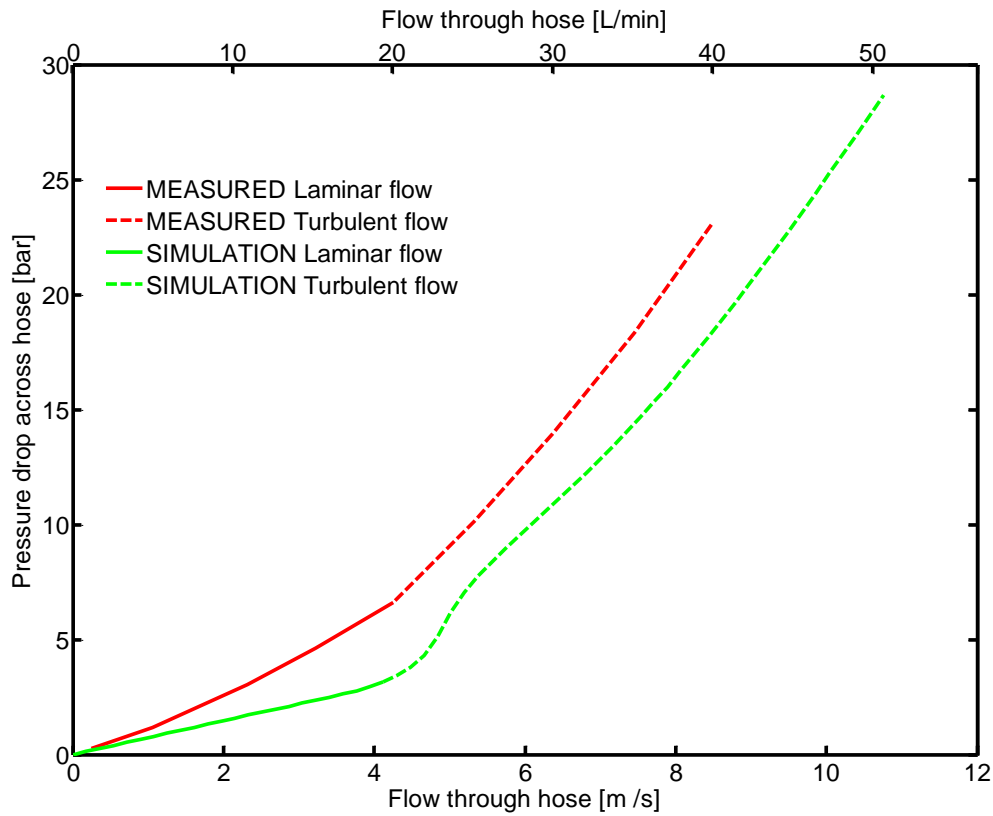


Fig. 10.27. Flow Vs Pressure drop across hose of synth es 32 at 60°C

10.2.6. Mineral oil 46

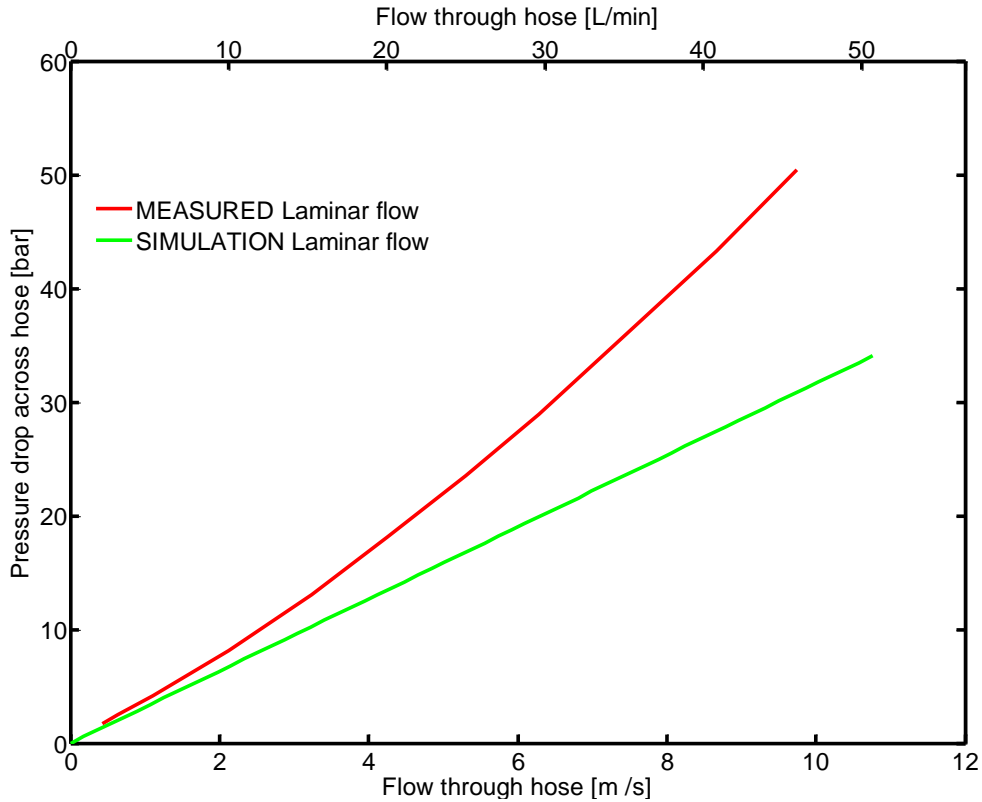


Fig. 10.28. Flow Vs Pressure drop across hose of mineral oil 46 at 30°C

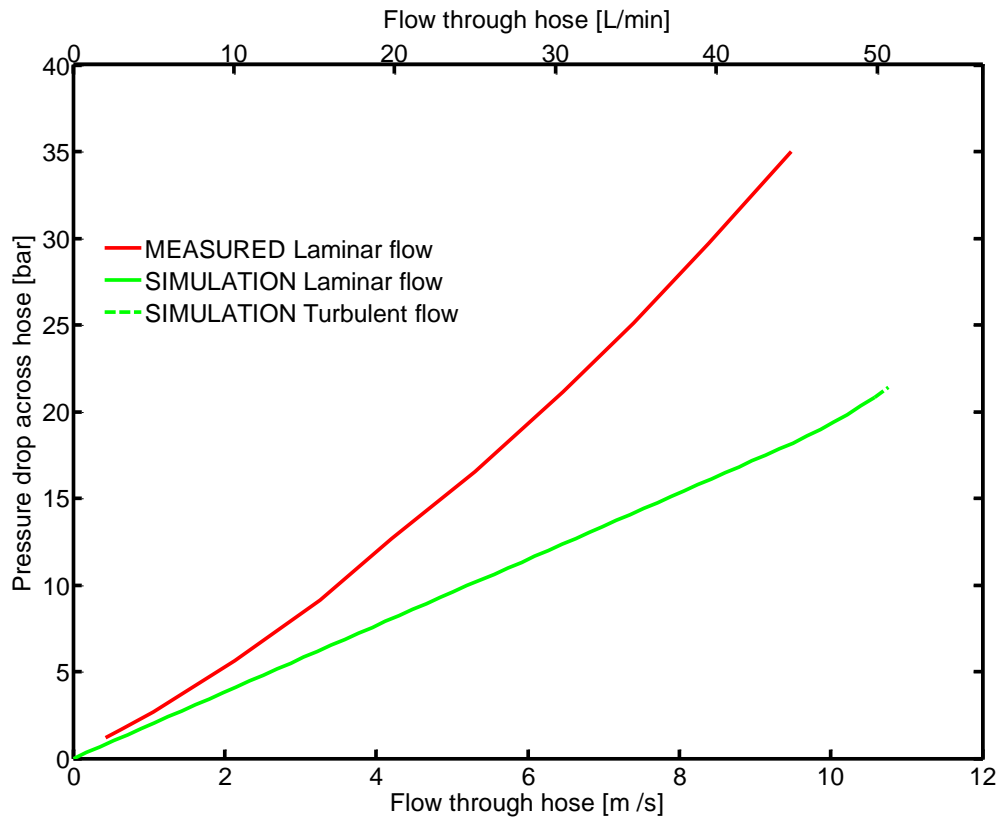


Fig. 10.29. Flow Vs Pressure drop across hose of mineral oil 46 at 40°C

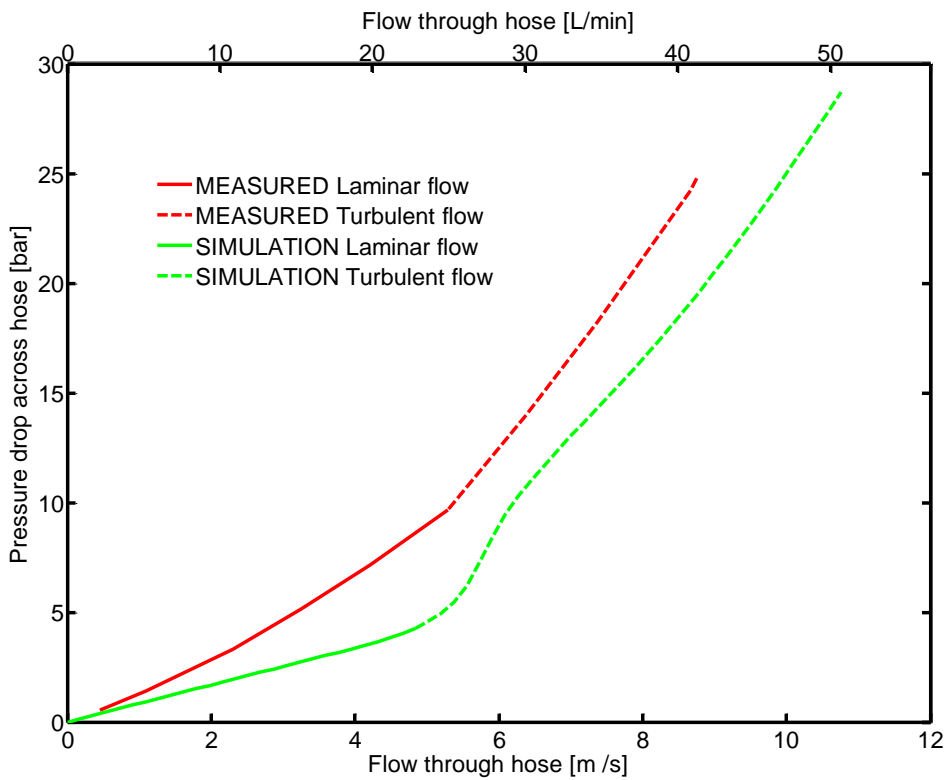


Fig. 10.30. Flow Vs Pressure drop across hose of mineral oil 46 at 60°C