A Novel Steam Engine Concept

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4F1824 – Project Course in Machine Engineering
School of Industrial Engineering and Management
January 2007

Fördjupningsarbete i Maskinkonstruktion 2007 **Ett modernt ångmotorkoncept** Hadeel Solaka		
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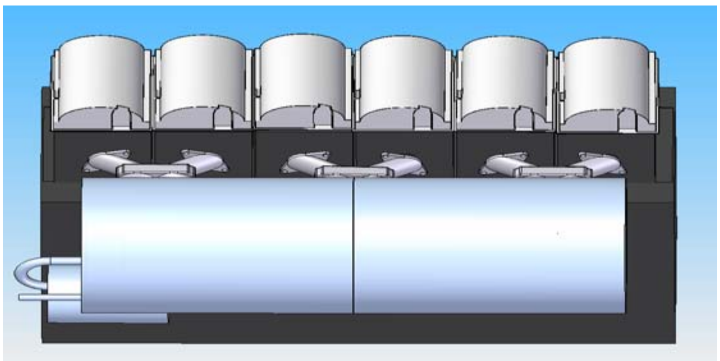
Sammanfattning

Projekt uppgiften var att bygga upp en solidmodell av en BC-hybrid och att använda denna modell för att visualisera systemets funktion och för att illustrera dess kompakthet.
Först skulle ett affärskoncept tänkas ut. Sedan skulle design och tekniska lösningar skapas, för att sedan leda till teknisk utvärdering och dimensionering.

Projektet handlade om uppbyggandet av en solidmodell av en modern kompakt ångmotor som utnyttjar avgasenergin från en lastbilmotor. Detta kallas för en BC-Hybrid (Bottoming-Cycle Hybrid).

För att kunna utnyttja avgasenergin från en lastbilmotor på ett effektiv sätt, kopplade ångmotorn direkt efter dieselmotorns utloppsportare(6-cylendrig). Detta medförde ett riskabelt koncept med ett vanligt dieselgrenrör eller med ett rakt grenrör. Kombinationen blev ett X-grenrör.

Resultat utav detta blev en designmässigt lämpad produkt som har goda förutsättningar att lyckas väl på marknaden. Hybrid ångmotor är i enlighet med vår projektidé mycket slitstark, kompakt och miljö vänligt.



Figur 1. Visar den slutliga kompakta lösning för BC-Hybrid

Project course in Machine Design 2007

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Date	Examiner	Supervisor
2007-May-02	Ulf Sellgren	Ulf Sellgren
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Abstract

Project's task was to build a solid model of a BC- hybrid and use the model to visualise system function and to illustrate its compactness.
First a concept had formulated. Then the design and the technical solution should be created, later on it will leads to the technical evaluation and dimensioning.

The theme of this project was to build a solid model of a modern compact steam engine. Which it make use of the exhaust energy from the diesel engine. This called for a BC-Hybrid (Bottoming-Cycle Hybrid)

In order to utilise the energy in an efficient way, the steam generator connected directly to the six in-lines cylinders' outlet head. This brought an outstanding challenge and a risky concept with the usual manifold pipe even with the single type manifold pipe. The combination of this was an X-type manifold pipe.

The results were a good and an appropriate design product, which has good conditions to be a successful product in the market. The BC-Hybrid steam engine is in accordance with the project's idea; it is very durable compact and environmentally product.

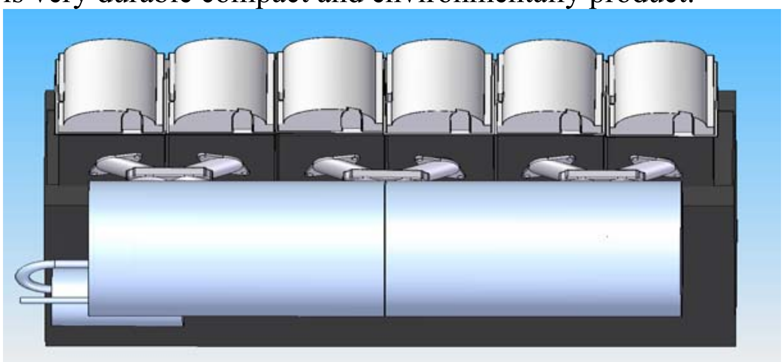

Figure 1. Shows the final compact solution for the BC-hybrid

Contests

1. Introduction

1.1 Background

Nowadays the hybrid solution is an effective popular concept for the automotive (such as heavy duty trucks) and which gives fuel-efficient up to 35 percent. The electric-hybrid technique is an example for the fuel-efficient. This method is designed that the vehicles have both an electric motor with batteries and an internal combustion engine. These tow engine and motor can cooperate during the operation of the vehicle in a good way by combining them parallel. In that way the parallel hybrid will expand its capacity substantially comparing with a series hybrids. The series hybrids are the substantially solution for the heavy hybrid trucks and which are examined these days. The electric hybrid motor has both advantages and disadvantages. One of the advantages is that the electric hybrid motors decrease the fuel consumption and among other things takes the advantage of the brake energy. However the electric hybrids technique can not utilise the waste heat from the ICE (Internal Combustion Engine). Another disadvantage of the electric hybrid concept is that it consists at least of tow motor. This means high fuel consumption at heavy load which leads to increase the temperature of the exhaust gas. [1 and 2]

RANOTOR *(www.ranotor.se)*, SAAB and Scania *(www.scania.se)* have studied the possibilities of the modern steam engine's applications for the automotive in the 70's. Later RANOTOR tried with Scania and Volvo to have a good comprehensive study of the possibilities to use the modern compact steam engine system as bottoming cycle in order to gain the waste heat in the exhaust gas stream from the heavy-duty truck's diesel motor. The project did not go as was planed because they applied the steam engine after the turbo turbine. The temperature is pretty low after the turbine during the low load and thus reduces the efficiency from the exhaust gas that will utilise to a useful work. [1]

In this project the ICE would be scaled down and exhaust manifold would be replaced by the heat recovery steam generator as well the turbine would be replaced by the steam expander in this way more energy efficient and a much less expensive thrust is realised. By putting these tow concepts together, a BC-hybrid would have tow advantages compared to each concept separately. This project was originally planned for a group work. Due to some circumstances it became one man job. Hence this project will cover and study the steam generator not the work of the expansion chamber, air-cooled condenser and feedwater pump.

1.2 Objectives

The aim of the project is to create a compact solid model of a BC-hybrid steam engine. Afterwards the model would be examined and visualized the complications and problems in the construction as well as strengthens of main parts that would be forced to the fatigue by temperature and pressure of the exhaust gases.

1.3 Delimitations

The BC-hybrid steam engine has some demands and limitations the most important of these are;

- The weight should be less than for the electric hybrid motor.
- The dimension of the steam engine should be taken inconsideration in order to place it perfectly in the (engine room).
- Emplacement of the catalytic converter.
- The choice of the material and the possibility of recycling.

2. Methodology

2.1 Computer Aided Design

CAD is used to design, develop and optimize product and it is also extensively used in the design of tools and machinery used in the manufacture of components. Solid Edge is powerful 3D CAD software that allows manufacturing companies to transform their process of innovation and achieve competitive advantage. Solid Edge delivers the benefits of a fully integrated and managed design discipline that eases that growing complexity of product design. [3]

2. 2 The ANSYS CAE (Computer-Aided Engineering)

The ANSYS software program is used in conjunction with 3D CAD solid geometry to simulate the behaviour of mechanical bodies under thermal/structural loading conditions. It supports engineering simulation solutions used to predict how product designs will behave in manufacturing and real-world environments. And its also integrated, modular and extensible set of solutions addresses the needs of organizations in a wide range of industries. [4]

2. 3 Heat Transfer Principle

Heat transfer is the science that seeks to predict the energy transfer that may take place between material bodies as a result of a temperature difference. Thermodynamics teaches that this energy transfer is defined as heat.
In many type of power and refrigerating cycles one is interested in changing a vapour to liquid or a liquid to a vapour depending on the particular part of the cycle under study. [5]

3. BC-Hybrid Technology

By controlling the waste heat from the ICE a BC-hybrid could takes in higher efficiency, higher specific power, cheaper than electric hybrids. A steam buffer and a modern high-performance steam are used to substitute the electric battery and the electric motor. Some new components should be developed in order to understand the BC-hybrid. The modern high performance steam engine system could absorb mainly two compact heat exchangers HRSG (Heat Recovery Steam Generator); Air cooled (Condenser) and an oil-free reciprocating piston engine operating at high pressure and with high-pressure ratios. [1]

3.1 Diesel Engine

The diesel engine is defined as an **internal combustion engine** is an engine in which the combustion, or rapid oxidation, of gas and air occurs in a confined space called a combustion chamber. This exothermic reaction of a fuel with an oxidizer creates gases of high temperature and pressure, which are permitted to expand. The defining feature of an internal combustion engine is that useful work is performed by the expanding hot gases acting directly to cause pressure, further causing movement of the piston inside the cylinder. [6]

a. How Diesel Engine Works

A diesel is an internal combustion engine that converts chemical energy in fuel to mechanical energy that moves pistons up and down inside enclosed spaces called cylinders. By moving the piston upwards, the air trapped inside is compressed, causing it to heat up. Before the piston reaches the top of its stroke (which called the Top Dead Centre) the pump and injectors spray a fine mist of diesel into the piston chamber. The intense heat of the trapped air in the piston chamber causes the diesel to ignite which forcing the piston down and producing the power stroke. The power stroke goes through the engine via the gearbox, wheels etc. [7]

b. Cycle Operation

There are two classes of diesel engine, two-stroke and four-stroke. Most diesels generally use the four-stroke cycle. The four strokes refer to intake, compression, and combustion and exhaust strokes that occur during two crankshaft rotations per working cycle of diesel engines. The four-stroke engine has intake valves rather than intake ports in the cylinder sleeve. As the piston moves downward from TDC the exhaust close while the intake valves remain open. In this case the fresh air rushes into the cylinder to fill the void left by the piston. When the piston reaches the BDC (Bottom Dead Centre) and start moving upward again, the intake valve is closed and compression begins. When the piston moves upward the air in the cylinder will be compressed and heated, the fuel injection begins and because the air in the cylinder is very hot, the fuel ignites as the piston moves up and past TDC. Later on it will begin its downward travel. The downward travel is the stroke power after the fuel ignites and it continues until the piston moves down and reaches the BDC at which time the exhaust valves open. At this point there is enough presser to force the exhaust gases from the cylinder to the exhaust manifold. As the piston reaches the BDC and starts moving upward the exhaust valve remains open and the upward movement of the piston continues to force exhaust gases from the cylinder and into the exhaust manifold. *Valve overlap* it is a period when the piston reaches near TDC when the intake valves open, so both valves remain open so the cylinder is completely charged with fresh air and ensures too that the cylinder is purged of all the exhaust gases. [8]

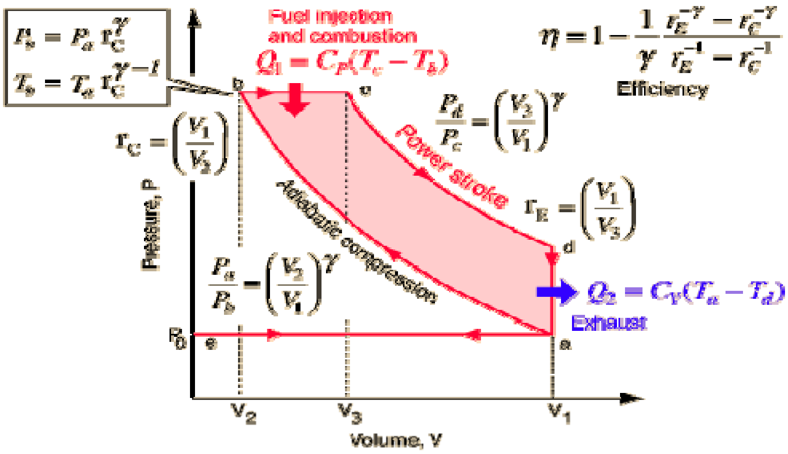

Figure 2. Shows a P-V diagram for four-stroke engine. [9]

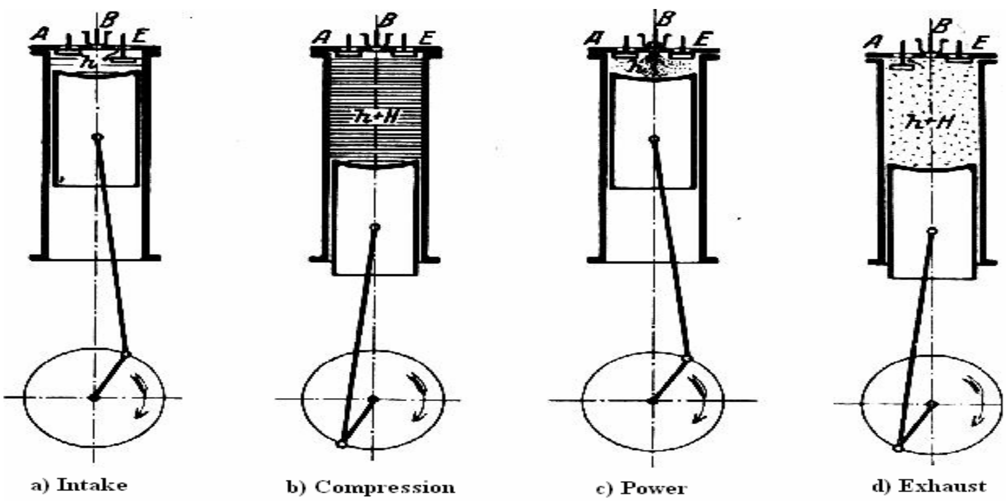

Figure 3. Shows one working cycle of a four-cycle engine. [10]

c. Thermal Efficiency for Diesel Engine

The thermal efficiency is a dimensionless performance measure of a thermal device such as an internal combustion engine. The thermal efficiency must be between 0% and 100%. Due to inefficiencies such as friction, heat loss, and other factors, thermal efficiencies are typically much less than 100%. For example, a typical diesel engine operates at around 45% thermal efficiency. It reflects the rate at which heat exchange surfaces transfer heat to the transfer medium (generally water or air). Three types of heat movement impact thermal efficiency. [11]

- Conductive/Convective heating surfaces – also referred to as secondary or indirect heating surfaces including all surfaces exposed only to hot combustion gases. [12]

- Radiant heating surfaces – also called direct or primary heating surfaces and consist of heat exchanger surfaces directly exposed to radiant heat from the flame. Radiant heat transfer is tremendously more effective than conductive/convective heat transfer and, contrary to commonly accepted belief, is where most of the heat transfer occurs in a boiler or forced air system. [12]

In this project have been used a six inline cylinder 12-litre diesel engines from Scania. They are the latest generation of engine management and injection systems to produce highly-efficient outputs.

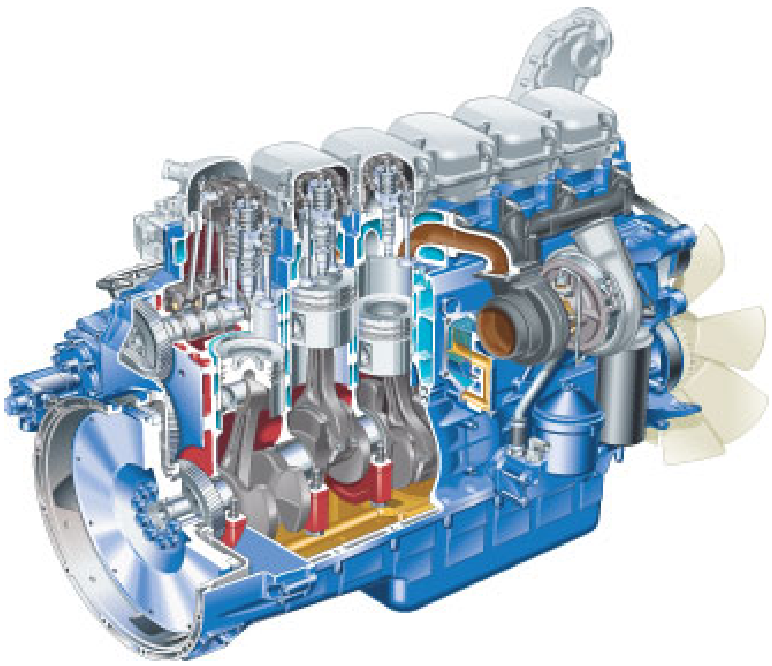

Figure 4. Shows the CAD model of the six inline cylinder 12-litre diesel engine. [13]

The air is compressed adiabatically in the diesel engine. This compression increase the temperature to the ignition temperature of the fuel mixture once the air is compressed. The ideal air is modelled as a reversible adiabatic compression followed by a constant pressure combustion process later an adiabatic expansion as power stroke and an isovolumetric exhaust(as its shown in *figure2*). *Table1* and *table2* are the data for the six in-line cylinder diesel motor that have been used in this project.

Average time= 10 ReadyTime	Patm_hPa	Speed_Rpm	Gastemp. before turbin cyl. 1-3 T1T_1-3_°C	Gastemp. before turbin cyl. 4-6 T1T_4-6_°C	pressure before turbine cylinder 4-6 P1T_4-6_Bar	pressure before turbine cylinder 1-3 P1T_1_3_Bar	Air flow mass in to engine Mair_HF_kg/s	FuelFlow_g/s	MomTot_Nm
13:43:09	1014,5	800,3	675,7	675	0,1848	0,281	0,110637867	6,719	1275
13:50:06	1014,2	999,5	655,2	656,4	0,4787	0,628	0,201337724	10,844	1853,8
13:58:48	1014,6	1200,4	604,5	608,7	0,697	0,874	0,272383322	12,65	1894,8
14:06:44	1014,6	1400,1	574	560,2	0,9814	1,18	0,349946444	14,391	1827,3
14:11:13	1014,6	1600,8	547,7	539,3	1,1669	1,349	0,395587213	15,107	1693
14:16:32	1014,5	1799,6	550,4	525,4	1,3821	1,545	0,436482086	15,708	1515,6
14:23:24	1014,6	2000,3	514,3	504,5	1,4234	1,559	0,447535882	14,998	1270,1
14:30:16	1014,7	2199,4	466,1	465,7	1,3277	1,424	0,439930544	13,096	964,5

Table 1. Shows the data for the six in-line cylinder diesel engine. [ref14]

12-LITRE ENGINES
DI 12 EMS is a turbo charged 4-stroke diesel engine
With EMS (Engine Management System and UI (Unit Injectors)).

Number of Cylinders	6 in-line cylinders
Volume of Cylinder	11.7 litre
Diameter of Cylinder	127 mm
Length of stroke	154 mm
Weight	1130 kg

Effect area for boats work

Continual operation (ICFN): 221 kW(330hk)-331 kW(450 hk) at 1800 rpm

Intermittent operation (IFN): 236 kW (320 hk)- 368 kW (500 hk) at 2100 rmp

Patrol boats with yearly operation time
386 kW (525hk) - 441 kW (600 hk) at 2100rpm
Patrol boats with short yearly operation time
404 kW (550 hk) – 478 kW (650 hk) at 2200

Table 2. Shows the data for the six inline cylinder 12-litre engines. [13]

Since the compression and power strokes are adiabatic the efficiency can be calculated from the constant pressure and constant volume process. Later on the output and the input energies and the efficiency can be calculated from the temperatures and specific heats:

$$Q_1 = C_p(T_c - T_b) \quad \textbf{(1)}$$

$$Q_2 = C_v(T_a - T_d) \quad \textbf{(2)}$$

$$\eta = \frac{Q_1 + Q_2}{Q_1} \quad \textbf{(3)}$$

In order to express efficiency in terms of the compression ratio and the expansion ratio

$$r_C = \frac{V_1}{V_2} \quad \textbf{(4)}$$

$$r_E = \frac{V_1}{V_3} \quad \textbf{(5)}$$

This can be rearranged to the form

$$\eta = 1 - \frac{1}{\gamma} \frac{r_E^{-\gamma} - r_C^{-\gamma}}{r_E^{-\gamma} - r_C^{-1}} \quad \textbf{(6)}$$

With $\gamma = 1.4$ for an air standard engine
$r_C = 15$ which r_C is a compression ratio
$r_E = 5$ which r_E is an expansion ratio

By using the data from *table1* and *table 2* and the value for γ, r_C and r_E , this will give an ideal diesel efficiency of 45% . The results are illustrated in *table3, figure5 and figure6*.

As well it is obvious from the data that the diesel engine has a low efficiency at certain load than at heavy load therefore it is important to develop a BC-hybrid engine which will take the benefits from the exhaust gas and increase the efficiency up to 10%.

Engine Speed [rpm]	Indicated Efficiency	Brake Efficiency	Moment [Nm]
2200	42,097	36,7357	964,5
2000	43,006	38,7763	1270,1
1800	44,3842	40,9412	1515,6
1600	43,668	40,8938	1693
1400	44,5034	42,0008	1827,3
1200	44,8477	42,4949	1894,8
1000	43,1481	41,2183	1853,8

Table 3. The efficiency for the six in-line diesel engine.

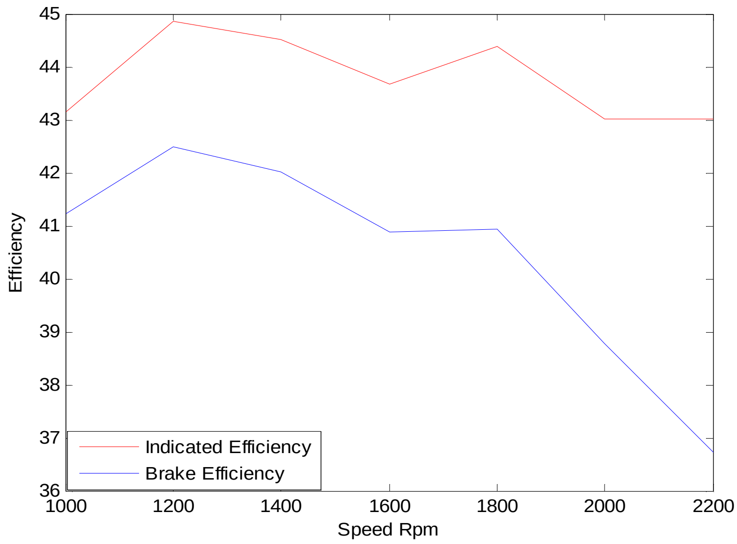

Figure 5. Shows the Efficiency as a function of speed.

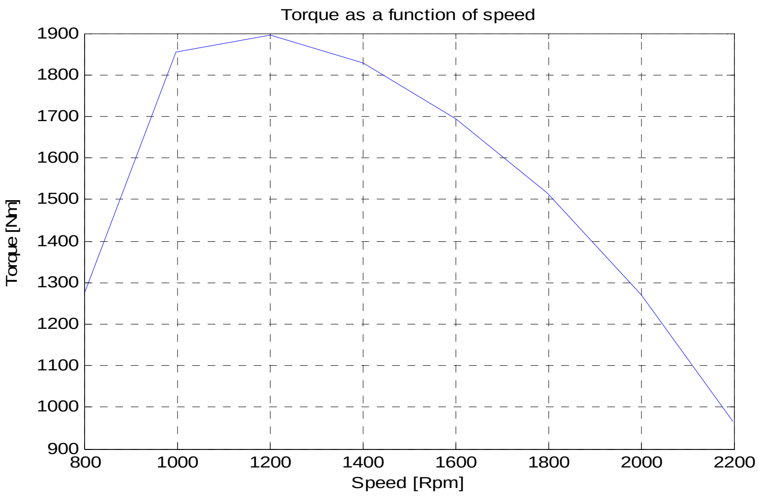

Figure 6. Shows the torque as a function of speed.

3.2 Steam Engine

A steam engine is a machine that changes the potential energy that exists as pressure in steam, and changes that to mechanical force. A steam engine requires a boiler to heat water into steam. The expansion or contraction of steam exerts force upon a piston or turbine blade, whose motion can be used for the work of turning wheels or driving other machinery. One of the advantages of the steam engine is that any heat source can be used to raise steam in the boiler; but the most common is a fire fueled by wood, coal or oil or the heat energy generated in a nuclear reactor.

Earlier the steam engine was a machine consisted of a closed container filled with water into which steam under pressure was introduced. This forced the water upwards and out of the mine shaft. Then a cold water sprinkler was used to condense the steam. This created a vacuum which sucked more water out of the mine shaft through a bottom valve. This method was invented by **Thomas Savery (1650-1715)**. Later a series of improvement and invention has been taken place in steam engine branch. The steam engine classifies after its work and the piston works. Here is some type of the steam engine: [15]

- **Vacuum engine** is called flame-licker or flame-gulper engines and work by drawing hot gasses or a flame into a cylinder to be cooled. One problem to be found is that if vacuum is required (vehicles that can be fitted with both petrol and diesel engines often have systems requiring it), a butterfly valve connected to the throttle can be fitted to the manifold. This reduces efficiency and is still not as effective as it is not connected to a venturi. Since low-pressure is only created on the over-run (such as when descending hills with a closed throttle), not over a wide range of situations as in a petrol engine, a vacuum tank is fitted. [15]

- **High pressure engines** in which the steam is raised in a boiler to a high pressure and temperature. It is then admitted to a working chamber where it expands and acts upon a piston. High pressure steam also has the advantage that engines can be much smaller for a given power range, and thus less expensive. [15]

- **Multiple expansion engines** use a series of double-acting cylinders of progressively increasing diameter and/or stroke and hence volume. These cylinders are designed to divide the work into three or four, as appropriate, equal portions for each expansion stage. Its use in steamships as by exhausting to a condenser the water can be reclaimed to feed the boiler, which is unable to use seawater. [15]

- **Uniflow engines** uses steam that flows in one direction only in each half of the cylinder. Steam always enters at the hot ends of the cylinder and exhausts through ports at the cooler centre. On of the disadvantages is that the large expansion ratio requires a large cylinder volume. To gain the maximum potential work from this a high reciprocation rate was required, typically 80% faster than a double-acting engine. [15]

- **The cutoff engine** is the point in the piston stroke at which the inlet valve is closed. Once the valve has closed the steam in the cylinder continues to expand but its pressure drops as it does so. It is difficult to apply it to the automotives because of the large size. [15]
- **Turbine engines** are used for the generation of electricity in thermal power plants (used to refer to the engine in ships, aircraft and other large vehicles.), such as plants using coal or fuel oil or nuclear power. Turbines rotate at very high speed, therefore are usually connected to reduction gearing to drive another mechanism, such as a ship's propeller, at a lower speed. A turbine rotor is also capable of providing power when rotating in one direction only. Therefore a reversing stage or gearbox is usually required where power is required in the opposite direction. [15]

- **Rotary steam engine** is an ideal power producer for automotive applications. The Wankel is a displacement engine that the steam passes through with no reversal in direction (uniflow) and the exhaust is from max displacement to min. displacement. The major problem is the difficulty of sealing the rotors to make them steam-tight in the face of wear and thermal expansion; the resulting leakage made them very inefficient. Lack of expansive working, or any means of control of the cutoff is also a serious problem with many such designs. [15]

The steam engine can easily be considered the single most important invention of the entire industrial revolution. It is obvious from all steam engines' type, that have been described above, that they could not be used in automotive application because of most of those inventions require either a large space, they can't work in many direction, they can't take the benefit of the exhaust gas or they require a high load in order to work effectively etc.

Therefore this project task is to develop and design a new concept of steam engine which is compact, doesn't require large room and with minimum weight and can make a benefit of the exhaust gas. But there are some challenges ahead like having more flexibility to create space in the vehicle.

Finally the basic system for the new concept (*Figure7*) is characterized by a steam generator supplying steam partially to the expansion in which is directly connected to the wheels and partially to a small engine in which drives the feed water pump. Later on the vapour is condensed in an air-cooled condenser system. The steam generator is directly connected to the ICE bye the manifold system which is not as the old fashioned one.
In order to describe how the system works so it is better to explain each part alone and how they work.

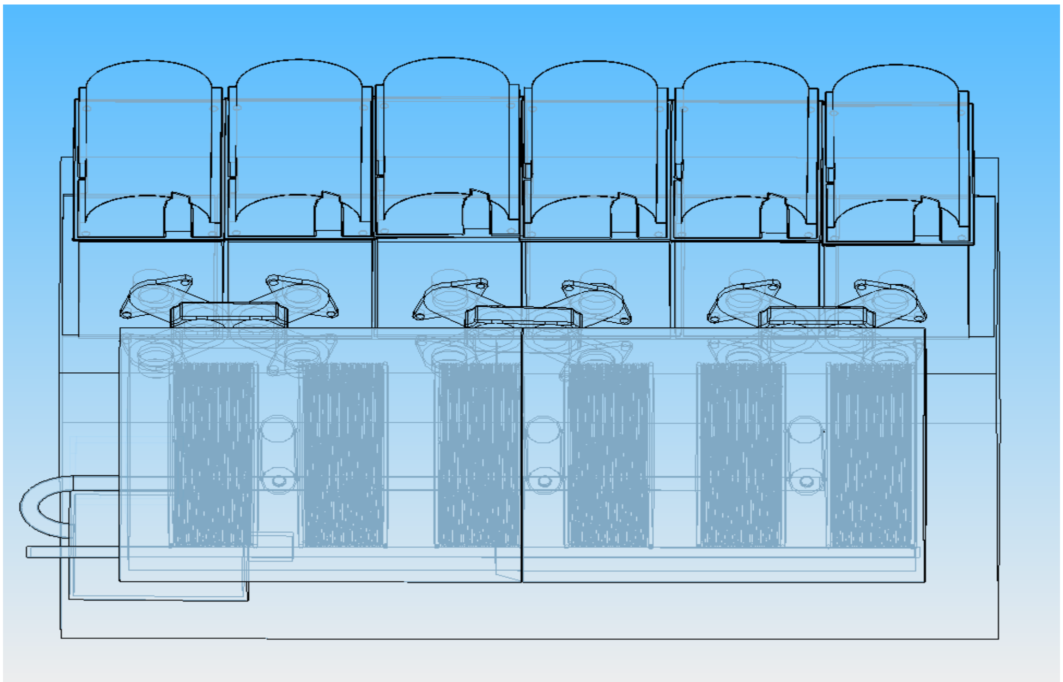

Figure 7. Shows the basic system for the new BC-hybrid concept.

a. Exhaust Manifold System

The manifold is a part of the engine that collects the exhaust gas from each cylinder in to one pipe. The engines with their cylinders arranged in-line usually have one exhaust manifold. The engines with V-type usually have tow separate exhaust manifold. The exhaust manifolds usually are made of cast iron or sometimes of tubular steel. The purpose of the exhaust manifold is to direct the exhaust gases that leaving the cylinder head to the exhaust system. The manifold acts as a joining point for the exhaust pipe.

In this project the exhaust manifolds are extremely important because they will route the exhaust gases from the cylinder directly to the steam generator. Thus it is vital to concentrate on a new design and construction that will deliver the exhaust gas flow parallel to steam generator. In this case the old fashion exhaust manifold is useless because it is designed in a way that has just one output head which is connected to the exhaust pipe. From the technical point of view, it is better to have six single pipes in order to utilise the heat from exhaust gas to heat the steam generator up. In this project has compared to kind of manifold in order to see which one has the high quality in delivering the heat from the exhaust gases.

i. **Description:** The exhaust manifold is made of stainless steel; it is like an X-type pipe about 106mm long, 60mm $Ø_{outside}$ and 40mm $Ø_{inside}$. The other exhaust manifold is a single pipe about 96mm long, 50mm $Ø_{outside}$ and 40mm $Ø_{inside}$ One end of the exhaust manifold mounts to the exhaust side of the cylinder head and the other one to the steam generator.*(see figure8 and figure9)*

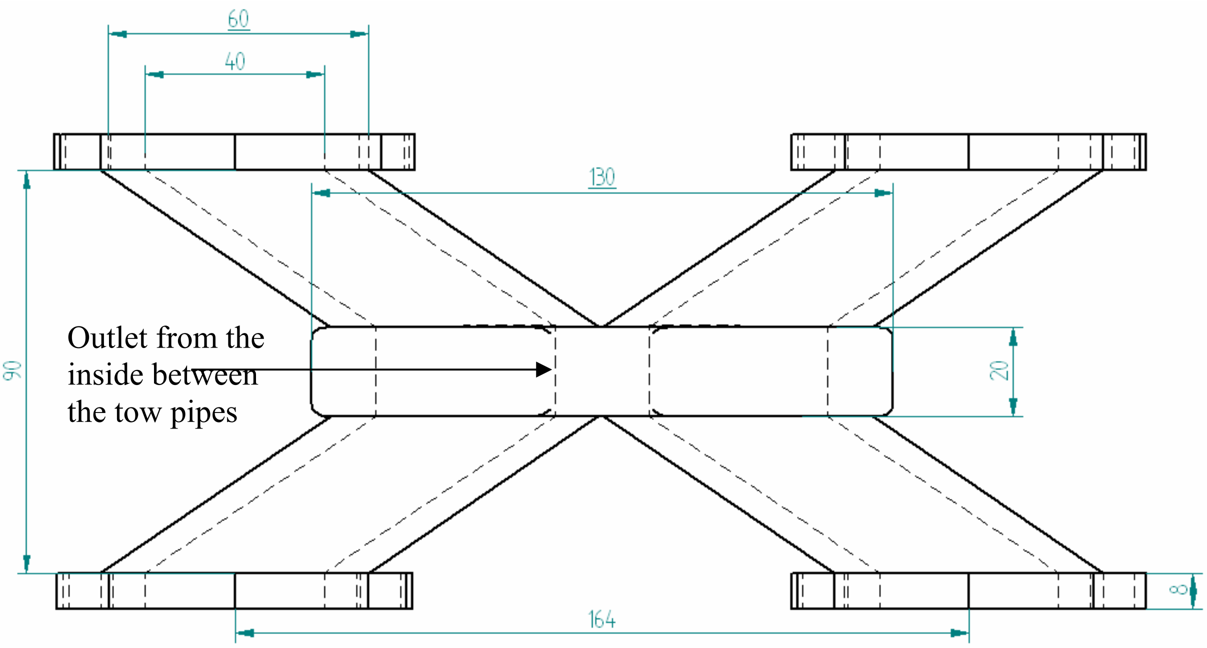

Figure 8. Shows the dimensions of the X-type manifold in [mm].

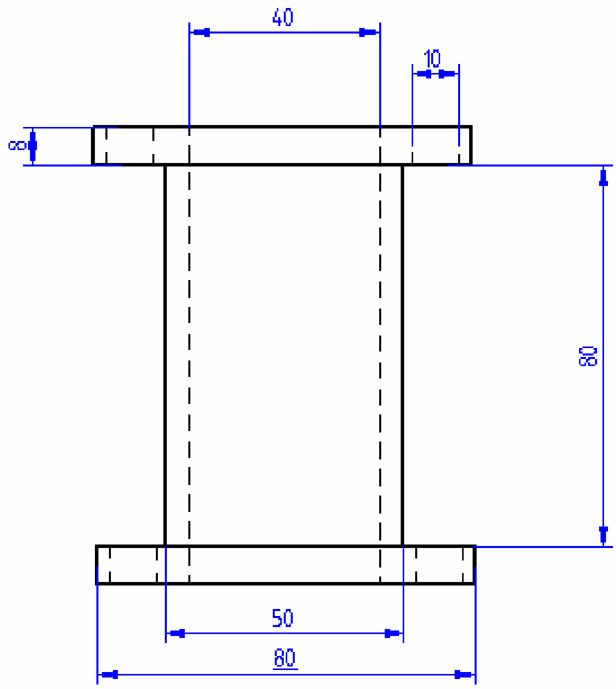

Figure 9. Shows the dimensions of a single type manifold in [mm].

ii. **Purpose:** The exhaust manifold routes the exhaust gases leave the cylinder head to the steam generator. As such, the manifold also serves as a connection point for the container that contains the steam generator. Depending on the engines configuration and which in this case has six in-line cylinder then it will be used 3 pair of the X-type manifold. It connects cylinder head 1 and 2 to the steam generator 1 and 2. And in case of single type manifold it will be used 6 pipes.

Heat flux for the manifold could be calculated:

$$q/A = - k*T/x \qquad (7)$$

Where

q/A is heat flux [W/m^2]
k is the thermal conductivity for the iron [W/m ^{o}C]
T is the exhaust gas temperature [^{o}C]
x is the long of the manifold pipe [m]

The value of k could be taken from a table, when the fluid is working at the T = 574 [^{o}C] and the iron tube is experiencing a temperature differential of 100 [^{o}C]

⇒ k = 40 [W/m ^{o}C]
x = 0.08 [m]

⇒ q/A = 50 k W/m^2

The Stress as well the strain could be calculated by using Hooke's Law:

$$\varepsilon_x = \frac{1}{E}[\sigma_x - v(\sigma_y + \sigma_z)] + \alpha\Delta T$$
$$\varepsilon_y = \frac{1}{E}[\sigma_y - v(\sigma_z + \sigma_x)] + \alpha\Delta T \qquad (8)$$
$$\varepsilon_z = \frac{1}{E}[\sigma_z - v(\sigma_x + \sigma_y)] + \alpha\Delta T$$

Where

E is elastic module [Pa], υ is Poisson constant, α is coefficient of length expansion [1/^{o}C]

Material	E [Gpa]	υ	α [1/^{o}C]	T_0 [^{o}C]	T_1 [^{o}C]	P [MPa]
Stainless steel	221	0.29	10.6e-6	550.4	100	0.1545
Cast iron	103	0.25	11e-6	550.4	100	0.1545

Table 4. The data for material choice for the manifold pipe

Assume the pipe as a thin-walled, and then the stress could be calculated:

$$\sigma_r = 0$$
$$\sigma_\varphi = \frac{Pa}{h} \qquad (9)$$
$$\sigma_z = \frac{Pa}{2h}$$

Where

a is radian of the pipe = 20 mm

h is the thickness of the pipe = 10 mm

By using the data from *table 4* and equation *(9)* ⇒

$$\Rightarrow \qquad \begin{aligned} \sigma_r &= \sigma_x = 0 \\ \sigma_\varphi &= \sigma_y = 309[kPa] \\ \sigma_z &= \sigma_z = 154.5[kPa] \end{aligned}$$

From the results above and by using equation *(8)* and data from *table 4*, the strain for both materials could be calculated:

Material	ε_x	ε_y	ε_z
Stainless steel	-0.0048	-0.0048	-0.0048
Cast iron	-0.0050	-0.0049	-0.0049

Table 5. The strain results for both materials of the manifold pipe.

In order to compare the results with ANSYS simulations, the ΔT putt to 550[^{o}C]

Material	ε_x	ε_y	ε_z
Stainless steel	0.0058	0.0058	0.0058
Cast iron	0.0060	0.0061	0.0061

Table 6. The strain results for both materials where ΔT 550[^{o}C]

b. Heat Exchanger Disc (steam generator)

Steam generator is a device used to boil water to create steam. The function of the steam generator is to transfer the heat from the reactor cooling system to the secondary side of the tubes which contain feed water. As the feed water passes the tube, it picks up heat and eventually gets converted to steam. The steam generators may also contain a steam separation region. [12]

The method that have been using here is called the cross-flow exchange. It is usually used in air or gas heat and cooling applications. Here the exhaust gas forced across the tubes bundle, while the another fluid which is water in this case is used inside the tubes for heating process. In this exchanger the gas flowing across the tubes called *mixed* stream, while the fluid in the tubes called unmixed. The fact that a fluid is mixed or unmixed influences the overall heat transfer in the exchanger because this heat transfer is dependent on the temperature difference between the hot and cold fluids. [5]

i. **Description:** The heat exchanger cylinder is made of stainless steel. The heat exchanger unit of the steam generator consists of 6 cylinders like. The cylinder is about 84mm long and 250mm∅.Each cylinder consists of three spiral wound tubes soldered together and parallel, through which the working medium flows. The inner diameter is 1mm and the outer diameter is 2mm. The ends of the tubes are connected to tow other tubes in which one of them transfer the cold water to the three tubes and the other one transfer the steam after the water have changed to the steam. The outer tubes have circa 5mm∅.*(see figure 10)*

Figure 10. The heat exchanger cylinder.

ii. **Purpose:** The heat exchanger (steam generator) has a main purpose and that is to change the liquid into the steam and transfer the steam to the expansion. Also it serves as tow connection points one for steam buffer that collects the steam and the second one for the water pipe.

In order to achieve compactness for the heat exchanger (steam generator) so it is important to have a small hydraulic diameter in order to have a beneficial influence. It is possible to pack more heat transfer surface in a given volume when the spacing between them reduces. The heat transfer coefficient α is given by:

$$\alpha = N_{nu} \cdot \lambda / d \qquad (10)$$

Where

N_{nu} is Nusselt number .

λ is the thermal conductivity for the medium transferring heat to/from the surface.

d is the hydraulic diameter.

Where N_{nu} can be calculated for the turbulent flow by:

$$N_{nu} = 0.023 * Re^{0.8} * Pr^{0.4} \qquad (11)$$

Where

Re = is Reynolds number

$\Rightarrow Re = \rho\, u\, d / \mu$

Pr = Prandtl number

Where the Pr, ρ, μ and λ theirs values could be taken from a table at the specific temperature. Then α can be calculated.

The temperature difference between the hot and the cold fluid varies between the inlet and the outlet. For the parallel-flow heat exchanger, the heat transferred through an element of area dA may be written

$$dq = -m_h c_h dT = m_c c_c dT \qquad (12)$$

c. Catalytic Converter

Catalyst is a substance that increases the rate of a chemical reaction by reducing the activation energy, but which is left unchanged by the reaction. Meanwhile catalytic converter can be defined as a machine used to reduce the toxicity of emissions from an ICE. They usually used in motor vehicle exhaust systems as well they can be used in generator sets, trucks, buses, train and other machines. Catalytic converter called convert hydrocarbons, carbon monoxide, and nitrogen oxides into harmless compounds, and it covers the stainless steel box mounted in the exhaust system. Inside the cover the catalyst either is ceramic or metallic based on activity coating incorporating alumina, ceria and other oxides and combinations of the precious metals platinum, palladium and rhodium.

Catalytic converters can either be an oxidation or three-way type. Oxidation catalysts convert carbon monoxide (CO) and hydrocarbons (HC) to carbon dioxide (CO_2) and water, but they have little effect on nitrogen oxides (NO_x) and particular matter.

$$2CO + O_2 \rightarrow 2CO_2$$
$$2C_xH_y + (2x+y/2)\ O_2 \rightarrow 2xCO_2 + yH_2O$$

While the tree-way catalytic converter operates in a closed-loop system together with a lambda, or oxygen, sensor to regulate the air/fuel ratio on gasoline engines. They have three tasks; reduction of nitrogen oxides to nitrogen and oxygen, oxidation of carbon monoxide (non greenhouse gas) to less harmful carbon dioxide (greenhouse gas) and oxidation of not burnt carcinogenic hydrocarbons to carbon dioxide and water.

$$2NO_x \rightarrow xO_2 + N_2$$
$$2CO + O_2 \rightarrow 2CO_2$$
$$2C_xH_y + (2x+y/2)\ O_2 \rightarrow 2xCO_2 + yH_2O$$

Catalyst activity increases with temperature *(see figure 11)*. A minimum exhaust temperature of about 200°C is necessary for the catalyst to "light-off". Higher temperatures are necessary for hydrocarbon conversion. LPG exhaust contains short carbon chain hydrocarbons which are more difficult to convert in the catalyst than those found in diesel or gasoline exhaust. [16, 17 and 18]

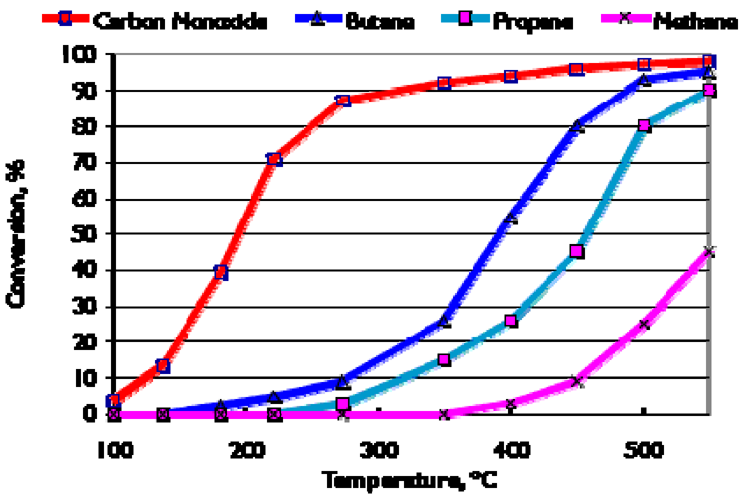

Figure 11. Conversion of CO and Hydrocarbons in Oxidation Catalyst. [18]

i. **Description:** Catalytic converter is made of ceramic *(see figure12)*. Converters contain a catalyst made from a noble metal such as platinum, palladium or rhodium. Catalytic converter usually is placed in the exhaust system but here it is placed in the middle of the heat exchange cylinder. It has strong-thin-wall substrates with cell densities of up to 1200 cells per square inch (186 cells/square cm) has been a major factor in the increasing efficiency of autocatalysis. It is about 84mm long and 250mm∅. (*see appendix figure 22*)

Figure 12. Catalytic converter and heat exchanger cylinder.

ii. **Purpose:** Catalytic converter’s job is to decrease the level of the harmful emissions in exhaust gases, as carbon monoxide, hydrocarbons and oxides of nitrogen. These emissions are very harmful and danger for both health and environment. It changes these harmful gases to harmless carbon dioxide, nitrogen, oxygen and water. As well the catalytic converter work as an extra area which will be used to heat up the water in the tube faster because the catalytic converter will be heated after 30 second. So it will work as an additional source for heating.

d. Steam Buffer

The Steam Buffer used for zero emission driving. It has the same capacity as electric battery when it comes to energy density 35 W·h/kg, but has a considerably higher power density, more than 10kW/kg. As an example, a 50 kg steam buffer gives, additional to the power output of the ICE, 500 kW for 10 seconds or 30 kW for 180 seconds. This steam buffer is equipped with a high temperature connection for steam, preferably with a temperature of 500° C and a pressure of 250 bars. [1 and 19]

i. **Description:** Steam buffer is made of ceramic *(see appendix figure 22 and 23)*. It is a cylinder like where its length is about 270mm and the outside and the inside diameter are circa 40mm respective 37mm. As well it has an outlet for the vapour which is almost a tiny cylinder that is 5mm long and the outer diameter is about 15mm and the inner diameter is 13mm. There are four inlets on the surface of the steam buffer which is connected to the outlets of the heat exchanger cylinders *(see firgure13)*.

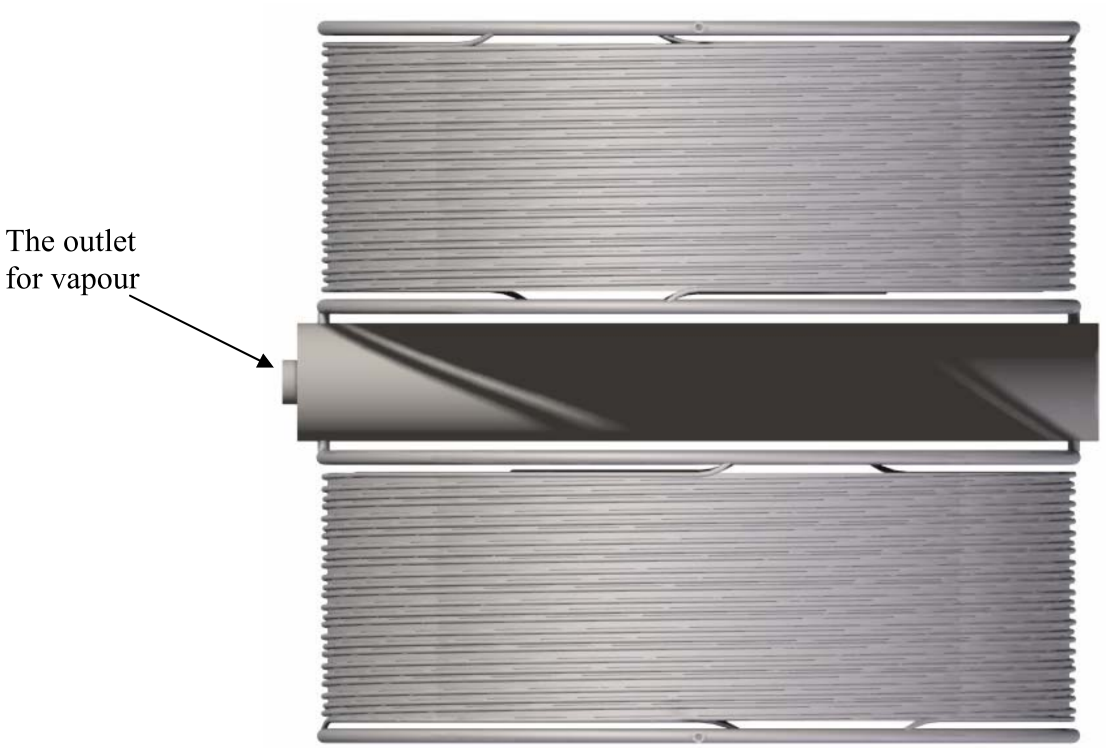

Figure 13. Steam buffer connected to tow heat exchange cylinder with catalytic converter.

ii. **Purpose:** The main reason of the steam buffer is that it works as a store that stores all the hot steam from the heat exchanger cylinders at a high temperature and pressure. Then use this pressure to drive the piston in the expansion chamber. As well the steam buffer works as a connection point for the steam pipe as well a connection point for the heat exchanger cylinders.

e. Expansion Chamber

In the expander, heat is converted into work. This type engine is made up of one expander. The expander increases and decreases volume in continues alternating cycle. At the start of increasing volume steam is admitted to the chamber producing a force that is transmitted to the output through mechanical linkages. At some point the steam is cut-off and left to expand (exception noted for nonexpanding engines) still producing force that is transmitted to the output but to a lesser and lesser degree as the pressure drops during expansion. At the end of expansion the expander is at its max volume (exception noted for uniflow engines). At this point the exhaust valve or port is open and the steam is allowed to escape the expander. The expander continues its cycle decreasing its volume forcing steam out to the exhaust. At some point the exhaust is closed and the residual trapped steam is compressed into the clearance space of the expander. [20 and 21]

i. **Description:** In the expander is planned to use a 5 –cylinder axial piston engine with cross-head and so called wobble-plate. The displacement is about 0.24 litres, stroke/bore is 38x40 mm, weight is circa 25kg and the total volume is about 24litre and it is made of iron.

The expansion and compression are isentropic processes. That is that they occur along constant entropy lines.

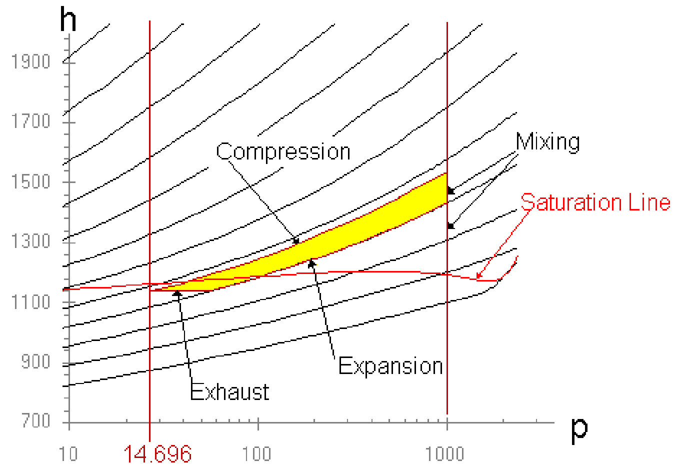

Figure 14. This is a plot of pressure verses enthalpy (BTU/lb) steam. [21]

To figure the thermal efficiency of the engine we calculate the work produced by one cycle of the engine and divide by the heat put into the admitted steam from the boiler. In thermodynamic cycle calculations it is common to figure the cycle based on a unit mass to simplify the calculations. Using a unit mass allows the use of specific volume in place of actual volume.

$Eff = (W_{admission} + W_{expansion} + W_x - W_{compression} - W_{pump}) / Q_{in}$

f. Air-cool Condenser System

The condenser is the change in matter of a substance to a denser phase, such as a gas (or vapor) to a liquid. Condensation commonly occurs when a vapor is cooled to a liquid, but can also occur if a vapor is compressed (i.e., pressure on it increased) into a liquid, or undergoes a combination of cooling and compression.The outlet of the steam from the steam generator exhausted either to the atmosphere or transmitted to the condenser, where it condenses the steam to the water. The steam is condensed in a liquid bath which is cooled by boiling-off to the air-cooled condenser. The air-cooled condenser can moreover work independently of the power output of the main engine and utilise the momentary cooling capacity to a maximum extent. The condenser is used of very small hydraulic diameters on the air as well as the steam side *(see figure 15)*. It is very compact and has low pressure drops. This system is combined by a battery as well as other comfort functions. [20]

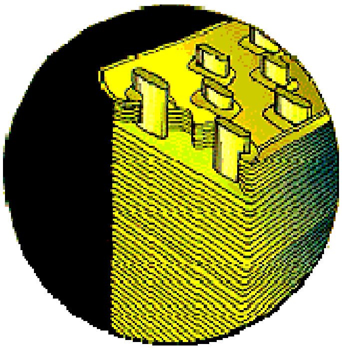

Figure 15. Air-cool condenser system. [22]

g. Feedwater Pump

Feedwater pump is a specific type of pump used to pump water into a steam generator. The water may be freshly supplied or returning condensate produced as a result of the condensation of the steam produced by the steam generator. These pumps are normally high pressure units that use suction from a condensate return system and can be of the centrifugal pump type or positive displacement type. Feedwater pumps range in size up to many horsepower and the electric motor is usually separated from the pump body by some form of mechanical coupling. For instance the GC boiler feed water pump in *figure16* and their data in *table7* could be a useful device for the steam generator.

Outlet Diameter	1.5" - 4"
Stage	2 - 10
Flow Rate (Q)	5 - 45 (m^3/h)
Total Lift Head (H)	46 - 288 (m)
Power Consumption	3 - 75 (kW)

Table 7. GC Boiler feed water pumps. [23]

Figure 16. Boiler feed water pump. [23]

4. Results and Discussions

In order to understand the BC-hybrid steam engine methodology and how to get the extreme advantage therefore it is necessary to develop some new components and to think widely than normal. With this new concept it is possible to take advantages from the exhaust gases temperature and reducing the fuel combustion of the ICE. Before the exhaust gases temperature where wasted to ambient air without making a useful work as well increasing the fuel combustion. From the results in *figure 5* and *figure 6* it seems that the diesel performing the very best efficiency 45% at 1200 [rpm] and with load 1900 [Nm] and with adapting the steam generator to the ICE, the efficiency can increase up to 10% that means, the new efficiency will be 55%. As well, the results from *table 3* shows that this concept will be more useful between 1200-1800 [rpm], which means that it is best for the long distance way.

In order to achieve the results as shown above in the first paragraph, we need a compact design of manifold pipe that will transfer all the heat of the exhaust gases from the head of the diesel cylinders to the exchange steam cylinders with minimum waste for the temperature to the atmosphere. Hence we designed tow models (*see figure 8 and figure 9*) of the manifold pipe and then we compared their ability to transfer heat as well their tolerance in an effective way bye using the ANSES program. This program simulated the total heat flux, stress and total deformations in each model *(see table 8)*. As well, we simulated on different materials like cast iron and stainless steel and comparing their results in order to choose the best one. We got these results from the simulation which is shown in *figure 17* and *figure 18* as well the *figures25-28* in the appendix.

Type	Single manifold (Cast Iron)	X-type manifold (Cast Iron)	Single manifold (Stainless Steel)	X-type manifold (Stainless Steel)
Total heat flux max. [W/mm^2]	8.732e-13	7.738e-12	2.543e-13	2.312e-12
Total deformation max. [mm]	0.335	0.9242	0.5206	1.432
Elastic Strain	0.006407	0.00807	0.009939	0.0124

Table 8. Results from simulation for both types of manifold pipes.

According to the results in *table 8*, the single-type manifold pipe which is made of stainless steel has the best value for the total heat flux. However I think if the aim is that each heat exchange cylinder will be heated as fast as possible so the X-type is the best for this mission. Because as we know the diesel engine’s cylinders goes 720 degrees that means from each cylinder’s head release the exhaust gases every 120 degrees. The diesel engine’s cylinders will release the exhaust gases first from cylinder 1 then 5, 3, 6, 2 and the last one 4. For instance if we had the single-type manifold so the exhaust gases will go from cylinder 1 to the heat exchanger cylinder 1 on the other hand if we had the X-type manifold then the exhaust gases will transfer from cylinder’s head 1 to the heat exchanger cylinder 1 as well 2, and so on for the rest of the cylinders.

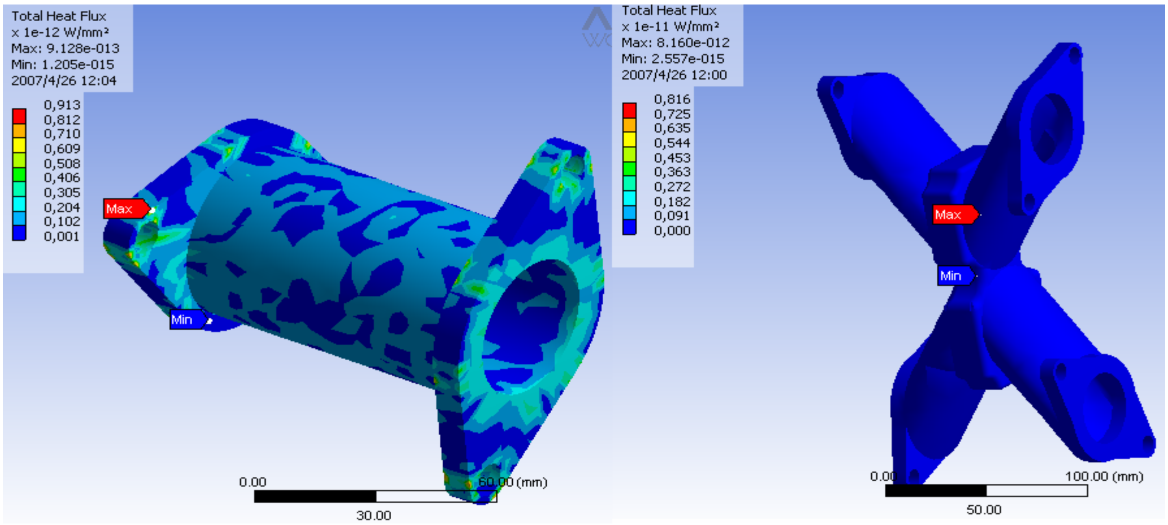

Figure 17. Total heat flux for the manifold pipes, the single type (to the left) and the X-type (to the right), in cast iron.

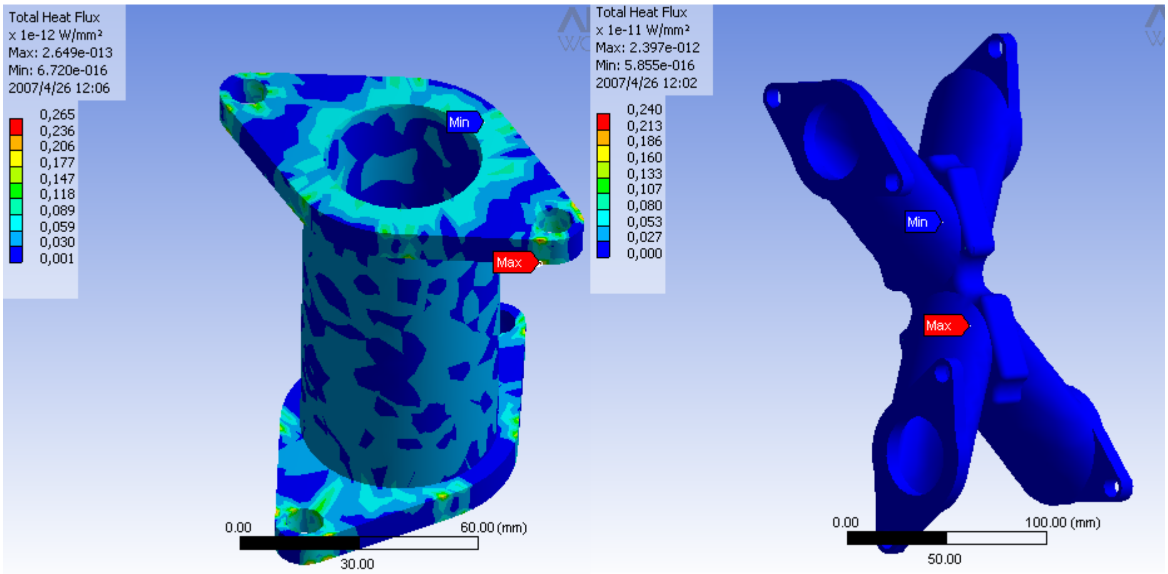

Figure 18. Total heat flux for the manifold pipes, the single type (to the left) and the X-type (to the right), in stainless steel.

In order to heat the heat exchange cylinders very rapidly, we need to increase the area by placing the catalytic converter inside the heat exchange cylinder *(see figure 12)*. From the heat transfer principle's point of view, this will increase heat flux and the system will work more efficient. But we must take in our consideration that the catalytic converter need high temperature to work effectively *(see figure 11)*. It needs at least about 200°C to start working. We chose the three-way type catalytic converter and it should be made of ceramic because if we chose to use a stainless steel catalytic converter then it will expand itself because of the temperature differences during the shift from day and night when the engine is still.
If the water can transfer to the vapour at 250°C and the catalytic converter "light-off" at 200°C, that means we need totally 450°C in order this system will work according to the *table 1* the minimum temperature is 466°C.

Finally to make use of the temperature in a good way, so it is important to think about the containers that will not transfer the heat to the atmosphere by radiation or convection. For this purpose we chose that the container should be made of cast iron and its thickness is circa 30mm and it is about 450mm long, as well 320mm$\varnothing_{inside}$ and 350mm$\varnothing_{outside}$*(see figure 19)*. On of the containers is designed to have a contraction after 450mm. This contraction length is about 30mm and the inside diameter respectively the outside diameter is 320mm respectively 330mm *(see figure24 in appendix)*. We have this contraction in order to avoid the extension and the expansion that will happen during the steam generators work. As we mentioned before that we want a compact system that will not take a big place in the engine's room as well it will configure outstanding with cylinder's head outlet for the diesel engine. And as we know the distance from the centre of the cylinder's outlet to another one is 164mm since we have a six in-line cylinder then the minimum length for the containers together will be 860mm.

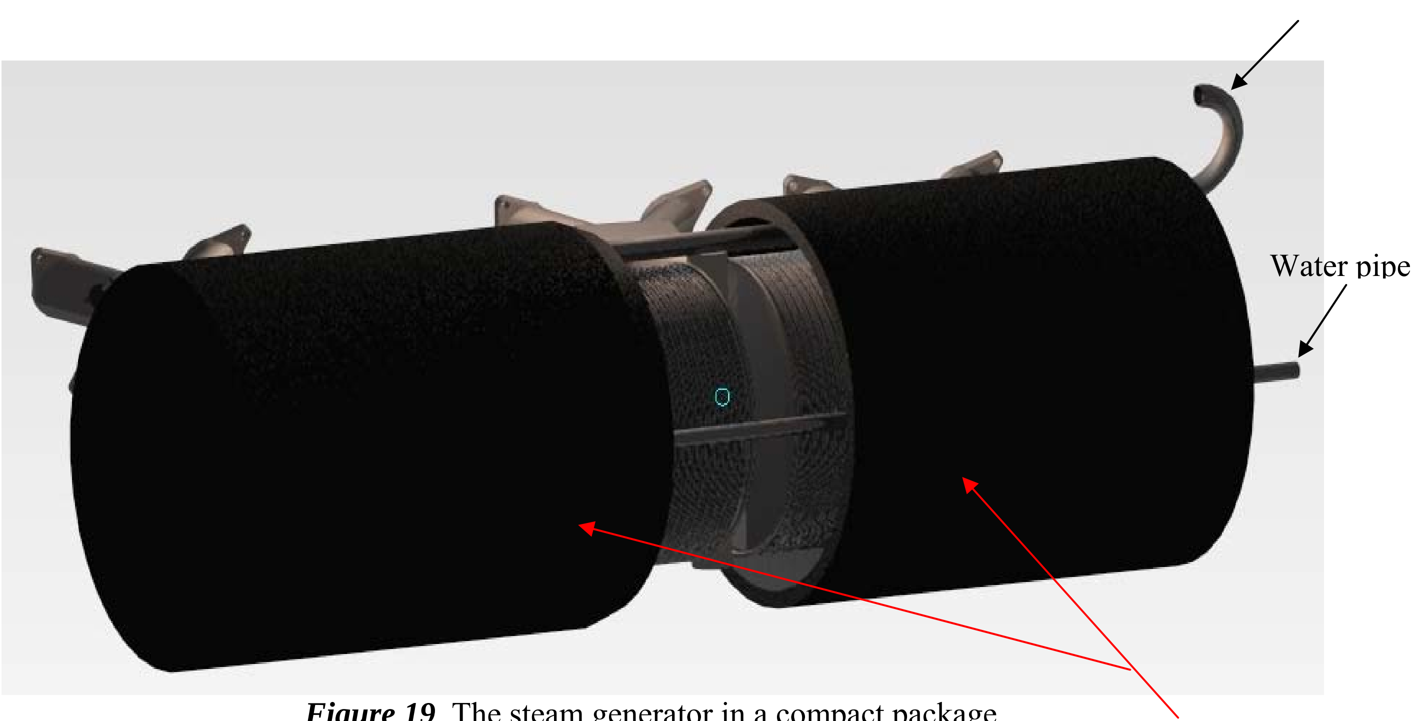

Figure 19. The steam generator in a compact package.

Quantity	Component	Type of material	Weight of the component [kg]	Total weight [kg]
6	Catalytic converter	Ceramic	6.695	40.17
6	Heat exchange cylinder	Stainless steel	0.255	1.53
3	Steam buffer	Ceramic	0.465	1.395
3	X-type manifold pipe	Stainless steel	3.112	9.336
1	Steam pipe	Stainless steel	0.471	0.471
1	Water pipe	Stainless steel	0.351	0.351
2	Container	Cast iron	54.333	108.666
			Total weight for steam generator	161.919

Table9. The total weight of the steam generator as one package.

From *table 9* we see that the total weight for the steam generator is much less than for the tow batteries for the electric motor in *figure 21*, appendix.

5. Conclusion and Recommendation

BC-hybrid steam engine enables the truck to be driven at all times and in all road conditions, laden, unloaded or part loaded, which is good for fuel economy. Any driver using BC-hybrid steam engine will achieve optimized driving for best economy.

The amount of exhaust emissions produced is directly related to the fuel used by the vehicle. As a result, with BC-hybrid steam engine, exhaust emissions will reduce in line with improving on-the-road fuel consumption.

The best application for this new BC-hybrid is for long haulage Scania's R-series *(see figure 20)* especially when they are part loaded.

Figure 20. Knights of old, Scania R 420 LA6x2/4MNA tractor units [24]

I suggest examining the expansion chamber closely as well the air-cooled condenser system. There are couple types of air-cooled condenser system which it should be studied more deeply and see which of those concepts are the best for the new BC-hybrid engine.

6. Future Work

There are many things that we can do and examine in future about the steam generator to make it a better product. There are tow important things that I have found extremely central in this project;

1- Both catalytic converters and heat exchange cylinders work efficiently at high temperature. Since the heat exchange cylinders utilise the temperature from the exhaust gases, this will leave a little amount of temperature used by catalytic converter. Therefore it is necessary to add a particle filter to the exhaust gas pipe; this will reduce the NO_x and other harmful gases from the exhaust gas successfully.
2- The air-cooled condenser system should be studied from many aspects, for instance safety, a better place for condensation and a room for air-cooled condenser system.

I would like to thank my teachers, colleges and my friends for their support

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Appendix

Grundfakta

Skriv ut

Bilmodell: Volvo FL sopbil, elhybrid/gas
Kategori: Lastbil
Bränslen: Biogas, Hybrid, Naturgas
Övrigt: Renhållningsfordon med hybriddrift. Framdrivning sker med natur/biogasmotor. Hydrauliken drivs med batterilagrad elektricitet. När bilen stannar kan lastbilsmotorn stoppas och aggregatets hydraulik köras med elmotorn. Ej i kommersiell drift, ett tiotal fordon i landet.

Fakta		Övrigt
Motorvolym	6 lit	
Motoreffekt	150 kW / 205 kWh	
Räckvidd	c:a 20 mil	
Elmotor	96 V	driver hydrauliken
Batterier	2 stycken á 48 V	vikt totalt 1250 kg
Motoreffekt	150 kW	
Katalysator	Ecat	minskar innehållet av metan i avgaserna
Generatorer	4 st 24 V generatorer för batteriladdning under drift	
Eldrift	Fordonets gasmotor stängs automatiskt av efter 30 sek vid lastning, som sker med hjälp av en elmotor. Batterier laddas under körning av gasmotorn samt nattetid i elnätet.	
Antal cylindrar	6	
Antal hjulaxlar	2	
Fordonsvikt	c:a 18 ton	
Lastkapacitet	c:a 5 ton	

Figure 21. A fact about how much is the weight for the electric hybrid motor.

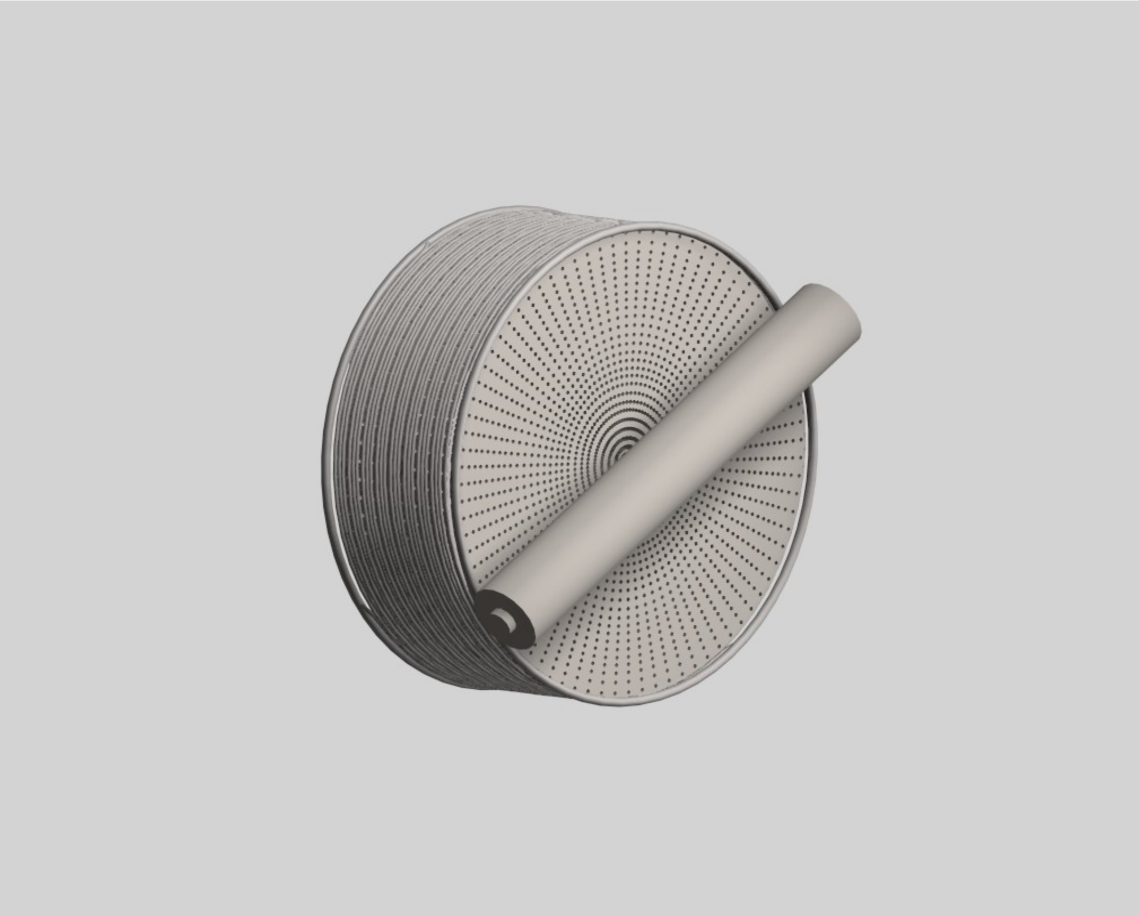

Figure 22. Catalytic converter, steam buffer and heat exchange cylinder.

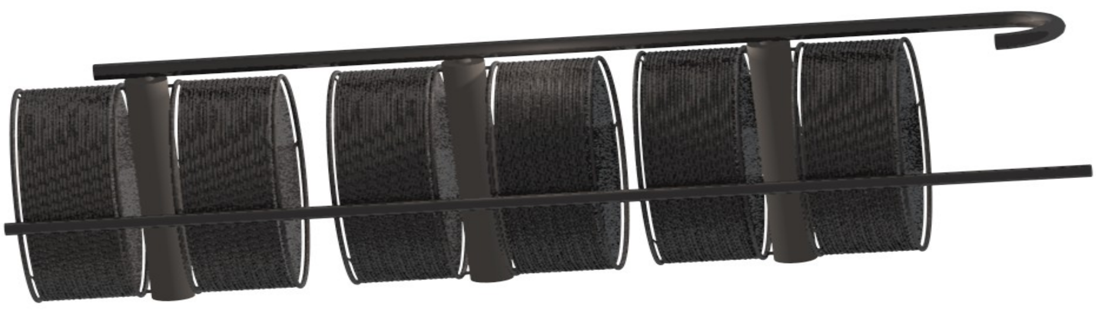

Figure 23. Shows the complete package.

Figure 24. The containers for the steam generator.

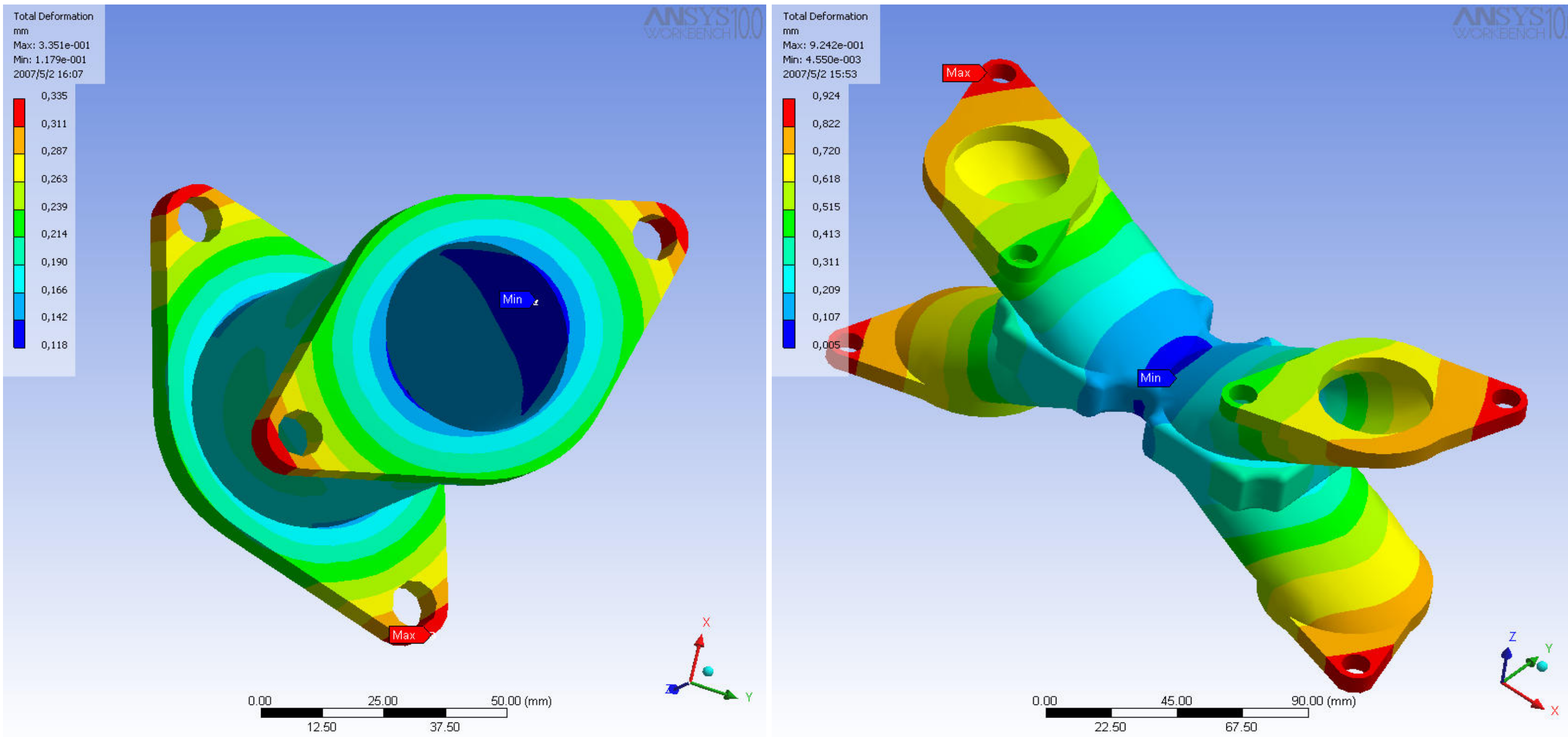

Figure 25. Total deformation for the manifold pipes, the single type (to the left) and the X-type (to the right), in cast iron.

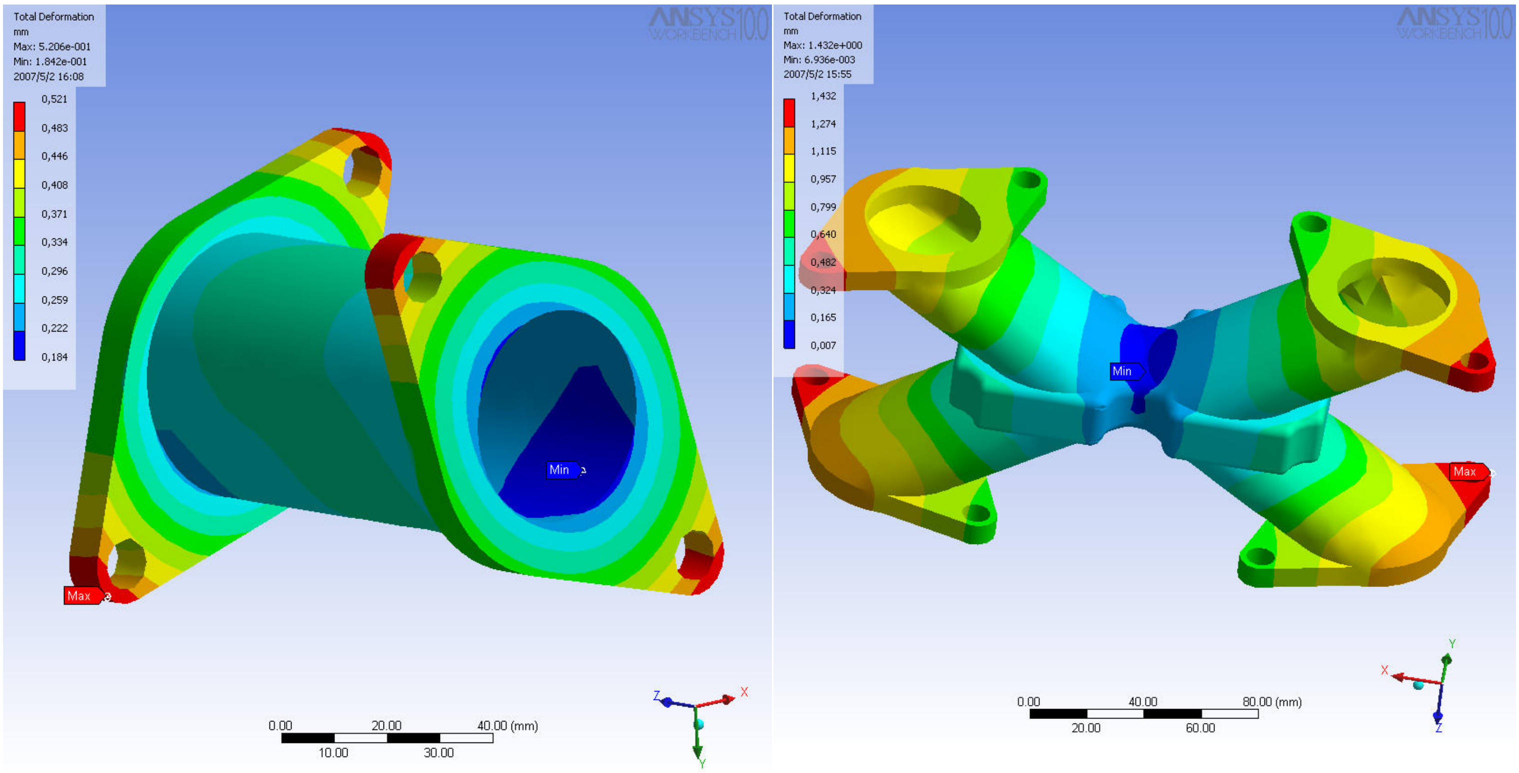

Figure 26. Total deforamtion for the manifold pipes, the single type (to the left) and the X-type (to the right), in stainless steel.

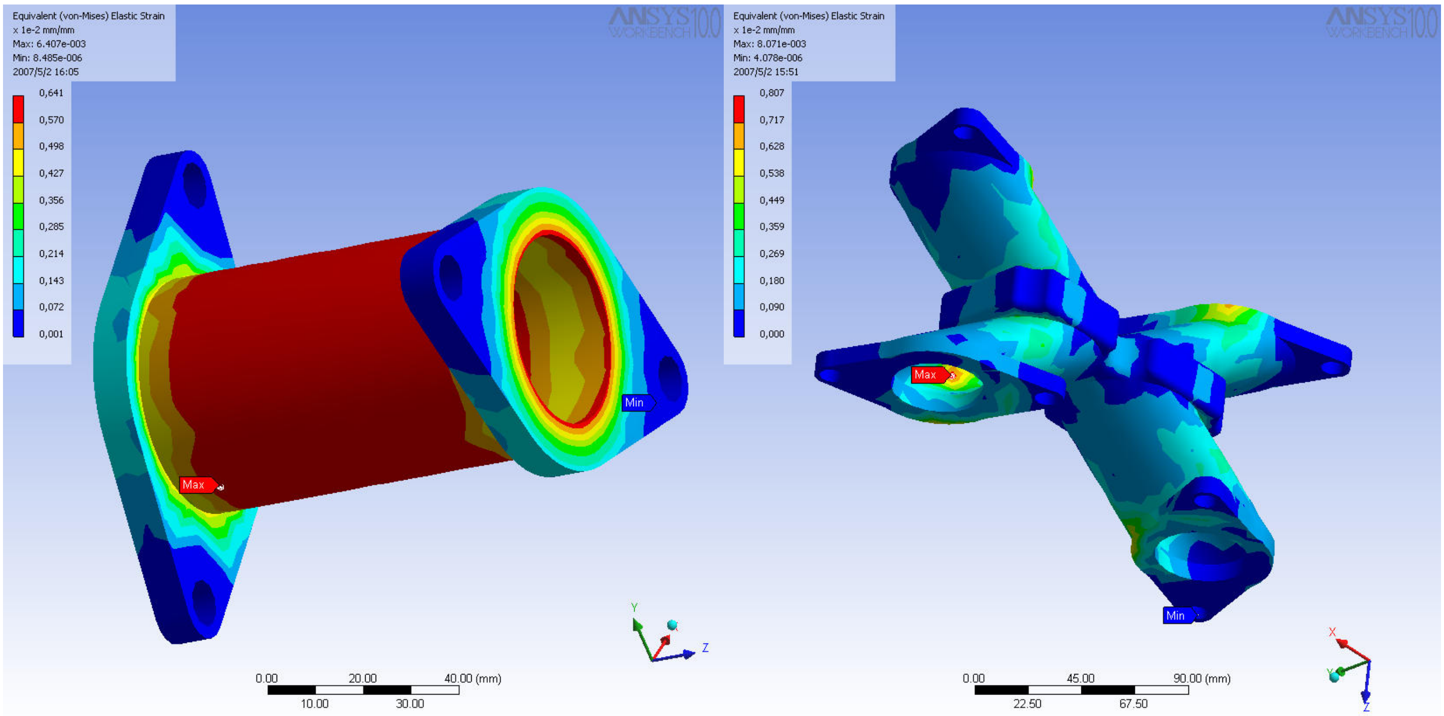

Figure 27. Elastic strain for the manifold pipes, the single type (to the left) and the X-type (to the right), in cast iron.

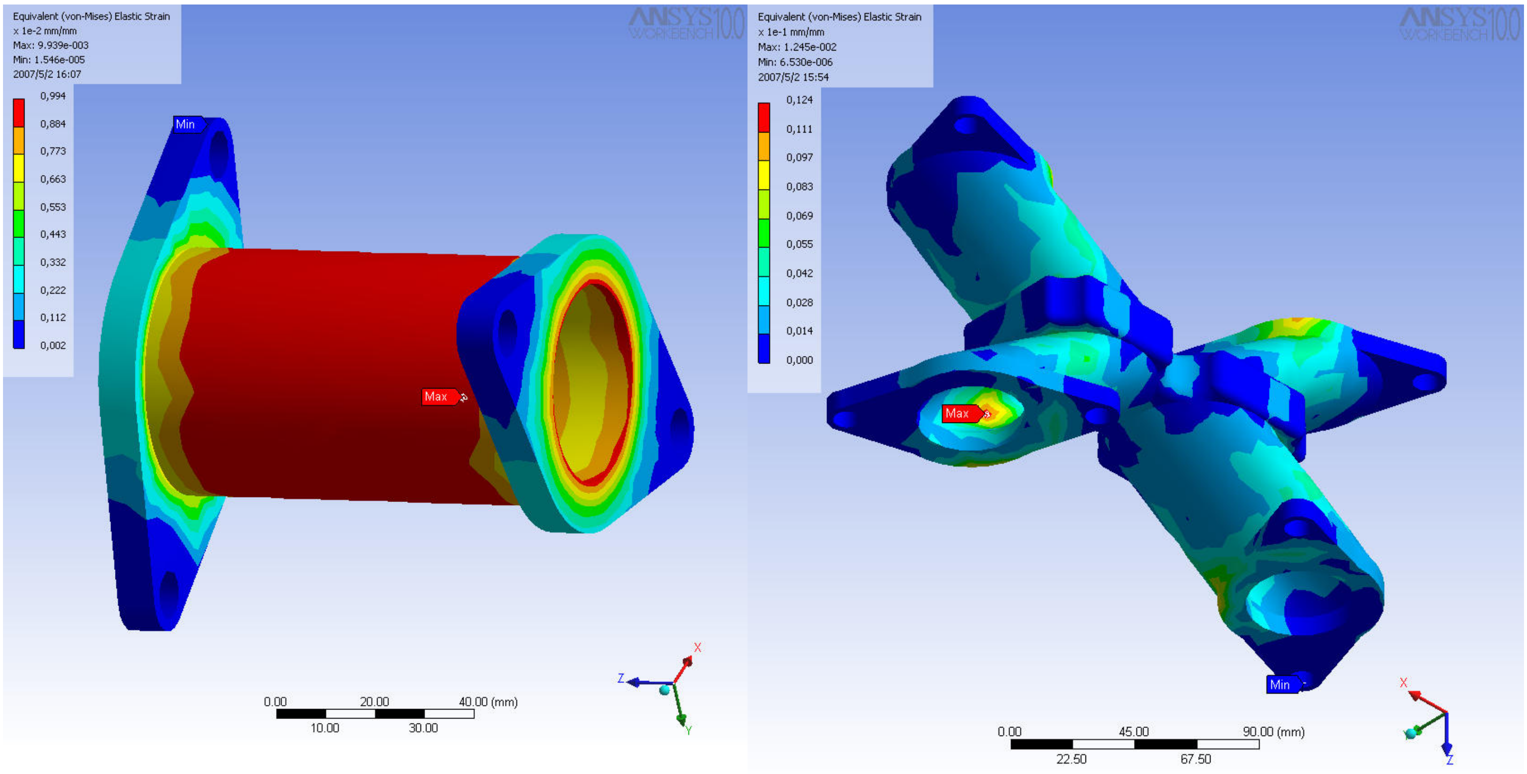

Figure 28. Elastic strain for the manifold pipes, the single type (to the left) and the X-type (to the right), in stainless steel.

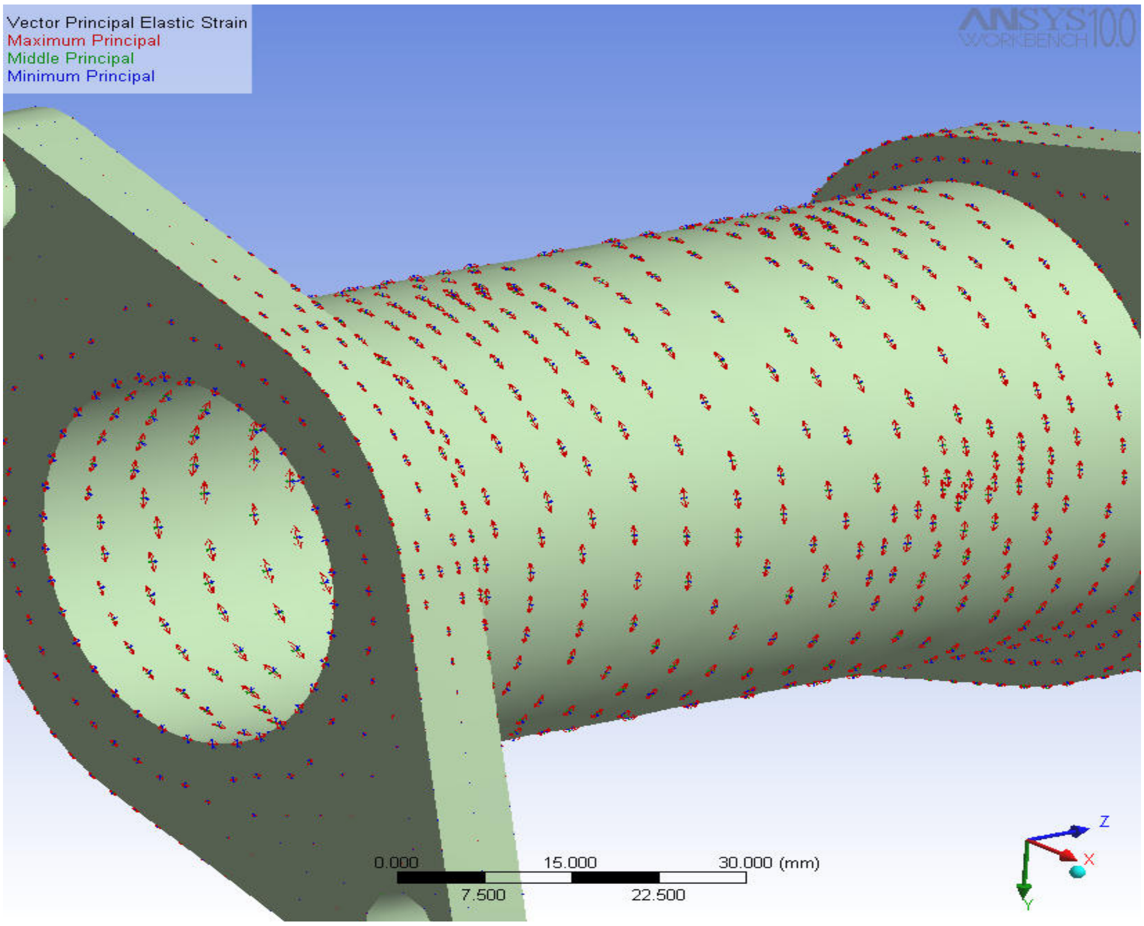

Figure 29. Vector principal elastic strain