CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Mechanical Engineering

MASTER THESIS

POWERTRAIN SYSTEM INTEGRATION FOR MINI-EXCAVATOR

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Abstract

Mostly in an automotive industry, for the development of any new machine from the existing machine, aim is to use mostly the parts which are in production or perform minimum modification in the existing parts or design less new parts. This leads to less investment as well as less time to build the new machine. And at the same time optimal and efficient use of energy at any operating point of the vehicle is also very important.

This thesis will show chapter wise, the sequential methodology, for the powertrain integration of a mini excavator.

In chapter 2, packaging proposals of different engineering systems such as exhaust system, hydraulic system, cooling system, air intake etc. are made as in initial stages, major vehicle and powertrain packaging constraints must be resolved. After the approval of proposals, these engineering systems are designed and optimized. Selection of the best suitable component has done for the respective systems. As there were major changes in the air filter system and cooling system, they are elaborated in the further chapters (chapter 3, chapter 4, and chapter 5).

In chapter 3, brief explanation and main components of air intake system has mentioned. CAD model of air intake system through CREO CAD software has proposed. Selected the suitable air filter based on performance curve and calculation. Air hoses are designed, and CAD modelled with considering its application, material, bearing temperature and pressure, maximum possible hose length, minimum possible bend radius etc.

In chapter 4, it explains why the pressure loss in the pipe and hoses occurs and how to calculate these losses in the air hoses of the air intake system and water (coolant) hoses in the cooling system by using the standard formulae. This helps for designing and CAD modeling of hoses. Here, we can also find the comparison between the calculated and KULI software pressure drop results. Modelling of cooling system through KULI software takes times because of unavailability of technical data of radiator and oil cooler at the earlier stage. Benefit of this calculation helps to do the design of the hoses under close approximation of pressure. Thus, helps in early CAD modelling and hose design, that’s saves a lot of time.

In chapter 5, it explains optimization of cooling system through KULI software and KULI results helps to select a suitable fan of different suppliers. This chapter includes basic heat transfer theory and brief explanation about the main cooling system components. KULI software overview, purpose, its modules, benefits, and applications are briefly explained. Simulation input calculation and KULI model is described. Finally, the simulation result, analysis and the selection of suitable fan from various fans has shown based on some important criteria. Chapter 6 and chapter 7, shows the conclusion and the future aspects.

Preface

This thesis report is the final requirement to complete the Master program, European Master in Automotive Engineering (EMAE), a program organized by Czech Technical University, Prague (Czech Republic). The enrolled student works on an automotive engineering project, provided by companies and research centers.

In this program, after three semesters of theoretical study, the fourth semester is dedicated to practical learning which is based on the implementation of built up theoretical concepts. Upon successful completion of the project along the internship, students will be awarded 30 ECTS credits. This master thesis was carried out at the Doosan Bobcat EMEA, Czech Republic.

Acknowledgement

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List of Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
ECTS	European Credit Transfer and Accumulation System
EMAE	European Master In Automotive Engineering
EMEA	Europe, the Middle East and Africa
OEM	Original Equipment Manufacturer
VE	Volumetric Efficiency

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1 Introduction

1.1 Background

For the development of any new machine, the aim of all the OEMs is to use mostly the parts which are in production or perform minimum modification in the existing parts or design less new parts. This leads to less investment as well as less time to build the new machine. Same approach is used in this thesis such as in case of packaging of machine, proposal of air intake system, and designing of the new parts.

We know in today's automotive industry, optimal and efficient use of energy at any operating point of the vehicle is very important. Thus, this thesis requires to make such a simulation model that will optimizes the cooling system and its results will help to select the important components such as cooling fan, heat exchanger etc.

1.2 Motivation

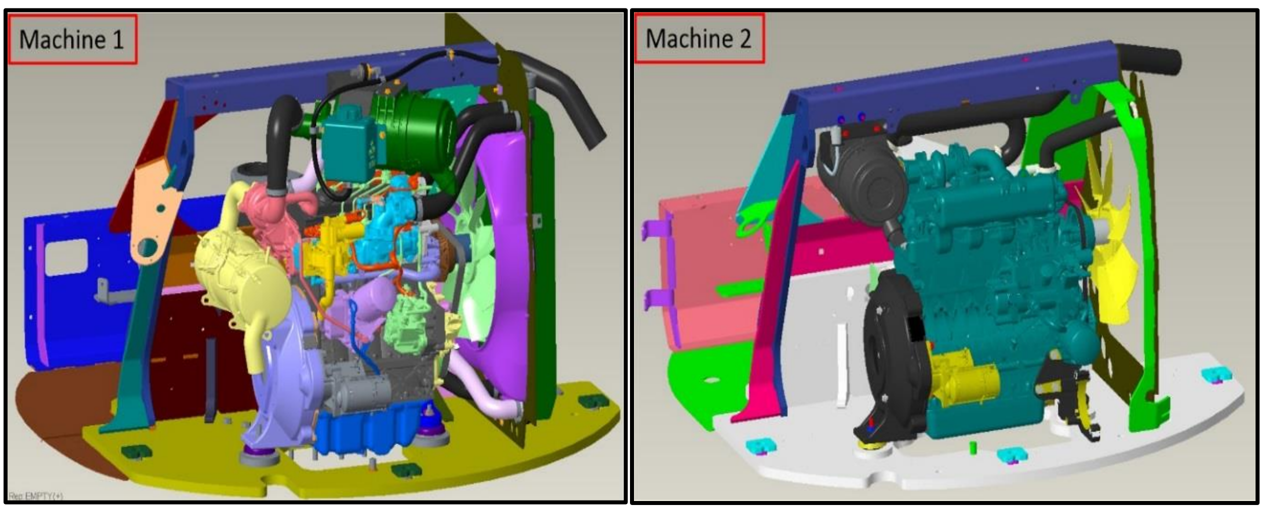


Figure 1 Motivation to create a new machine from the existing machines.

A new mini excavator need to be built for the middle east market. The motive of the manufacturer is to make cheaper machine, means minimum modification from the existing machine and its engine can be used with less stringent in terms of exhaust emissions.

We have two machines, machine 1 and machine 2. Both machines have different upper structures. And both machines are with different engines, engine 1 and engine 2 with following specifications:

	Engine Spec comparison	
	Engine 1	Engine 2
1	More fuel efficient	Less fuel efficient
2	Less Exhaust emissions	More Exhaust emissions
3	Costly	Cheap

Table 1 Basic Engine comparison for machine 1 and machine 2

Preferred solution was to use the same upper structure of machine 1, and engine and its accessories of machine 2. To achieve this, the goal was to design lesser new parts or to do minimum modification in existing parts or best to use the existing parts which are in production. And cooling system need to optimize through some modelling to select its important components.

1.3 Objectives

The four main objectives, which are given below, are explained in further chapters, in detail, in the sequential order and finally the conclusion is summarized at the end.

1.3.1 Packaging of mechanical engine and its accessories into the existing mini-excavator

1.3.2 Proposal of air intake system, selection of proper air filter, and design of air hoses.

1.3.3 Air intake system and cooling system - pressure drop calculation.

1.3.4 Optimization of cooling system using KULI Software and selection of suitable fan.

2 Packaging of mechanical engine and its accessories into the existing mini-excavator

2.1 Proposed CAD model of a new machine

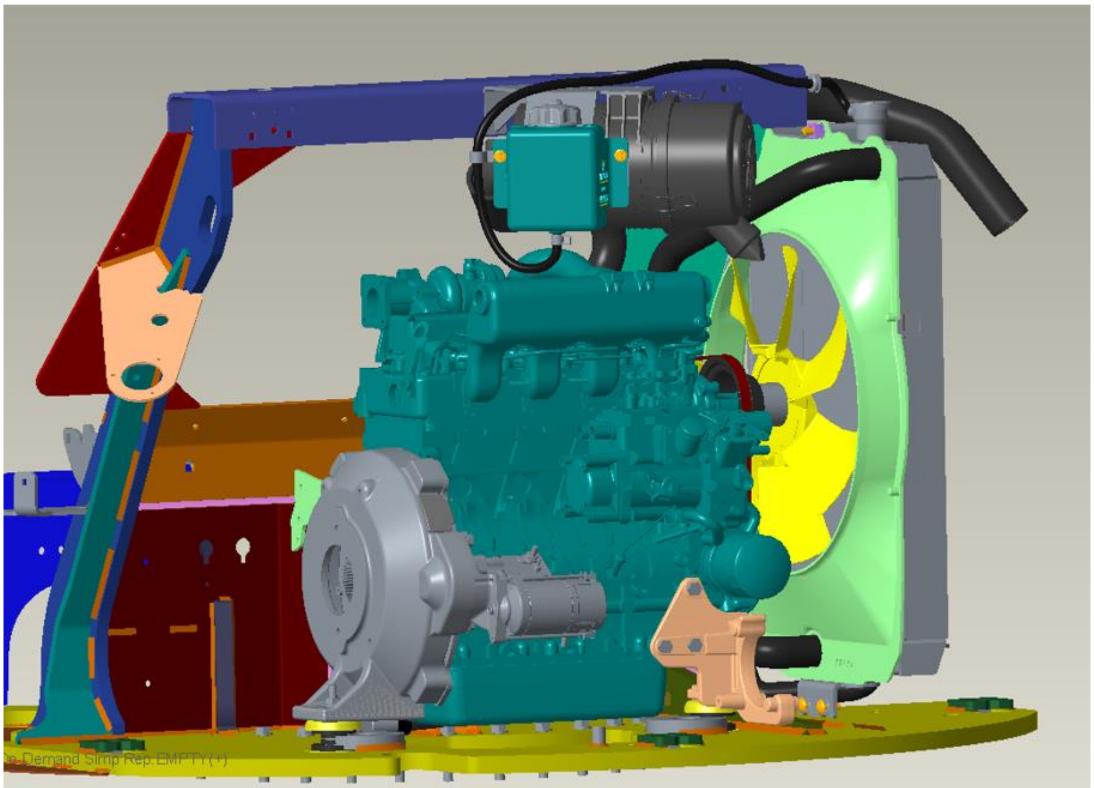


Figure 2 Proposed CAD model

In the above figure 2, the proposed CAD model is made, using CREO CAD software. This CAD model has made after the approval of various proposals, of different engineering systems, that are discussed further in this chapter. As discussed in the motivation chapter, we kept the same upper structure of existing machine 1 and done packaging with the engine and its accessories of machine 2.

During this modeling, there are few parts that are newly designed such as fan shroud, tail pipe, and hoses for air-filter system and cooling system. Some parts that are modified such as air filter, rear mount (grey colored in above figure 2) and its mounting. And the rest of the parts are kept as it is with the same positioning.

At first, the engine positioned on the front mounting via front mount (orange colored in above figure 2) with respect to the heat exchanger and then the fan shroud designed.

Later air intake system, cooling system, exhaust system, hydraulic system etc. were positioned with keeping 25 mm of clearance from their surroundings to avoid collision due to vibration, at running condition of engine.

2.2 Packaging proposal for the exhaust system

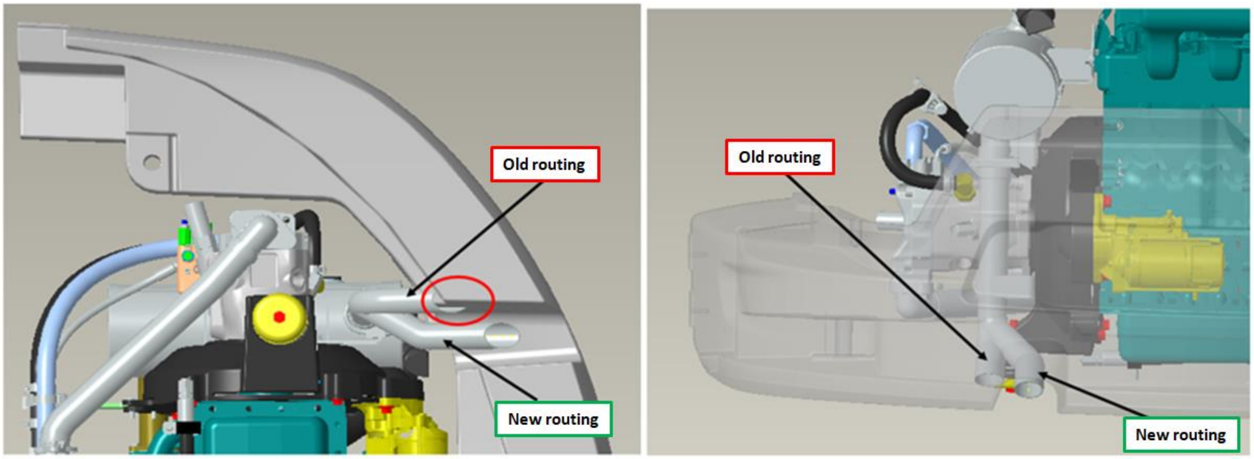


Figure 3 Overlapping of old tail pipe and proposed new routing

The exhaust system is used from the accessories of engine 2 and its muffler tail pipe was in collision with counterweight of machine 1.

Therefore, the proposed and feasible solution for the new machine is to have a new routing of muffler tail pipe as shown in the above figure 3.

2.3 Packaging proposal for the hydraulic system

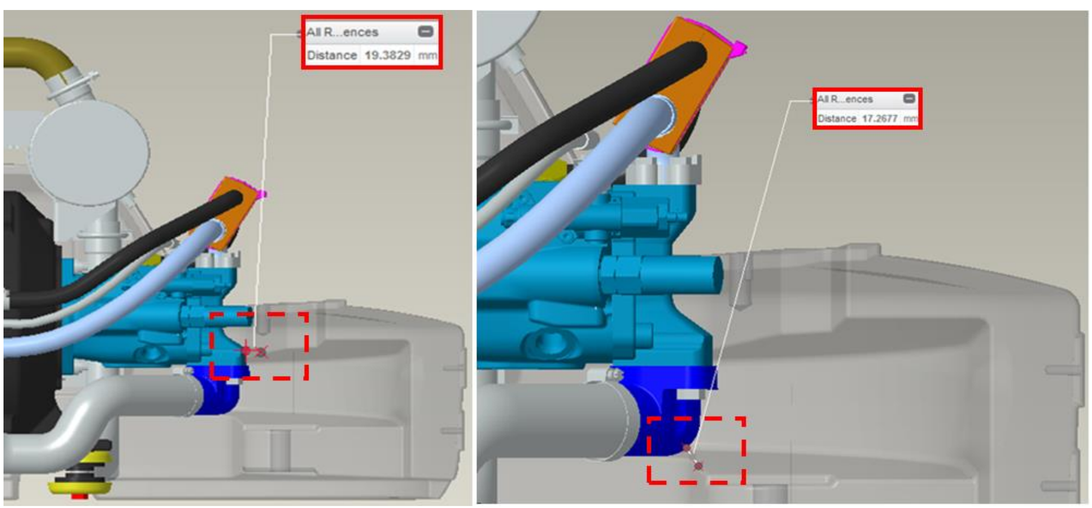


Figure 4 Lesser clearance from the required 25 mm between hydraulic pump and counterweight

The hydraulic pump is used from the accessories of engine 2 and counterweight of machine 1. And we can see in figure 4 that it is not satisfying the 25 mm clearance criteria from its surroundings.

Therefore, the proposed and feasible solution for the new machine is to have a small cut in the counterweight of machine 1.

2.4 Packaging proposal for the cooling system

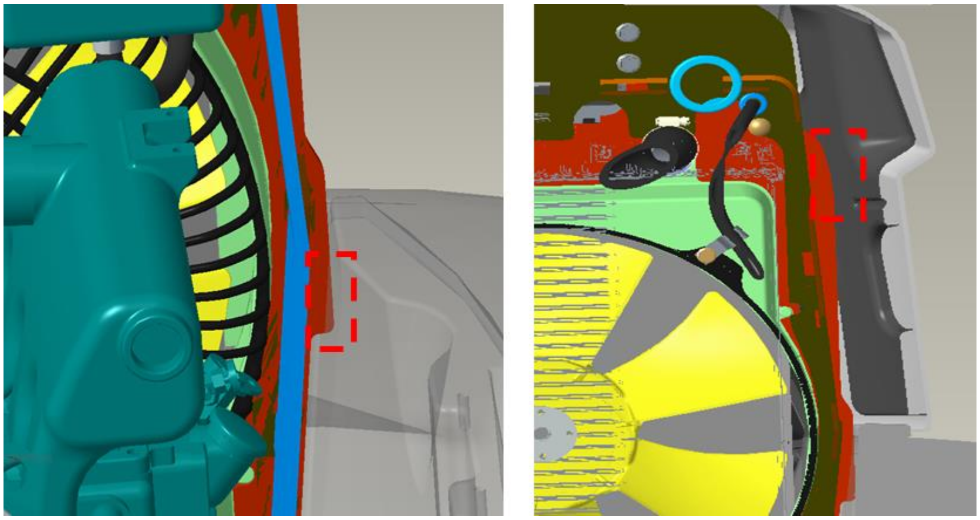


Figure 5 Collision of machine 2 cooler frame with tail gate stiffener and counterweight

The cooler frame is used from the machine 2 and there is a collision with tailgate stiffener and counterweight of machine 1 as shown in the above figure 5.

This proposal was rejected because while using the machine 2 cooler frame would leads to change in many components such as tailgate stiffener, counterweight, heat exchanger etc.

Therefore, the proposed and feasible solution for the new machine is to keep the same cooler frame of machine 1 and to design a new fan shroud and radiator hoses with having sufficient minimum length of hoses so that they will not collide with other components and will stretched during engine running conditions.

Newly designed fan shroud and their radiator hoses are shown in the below figure 6.

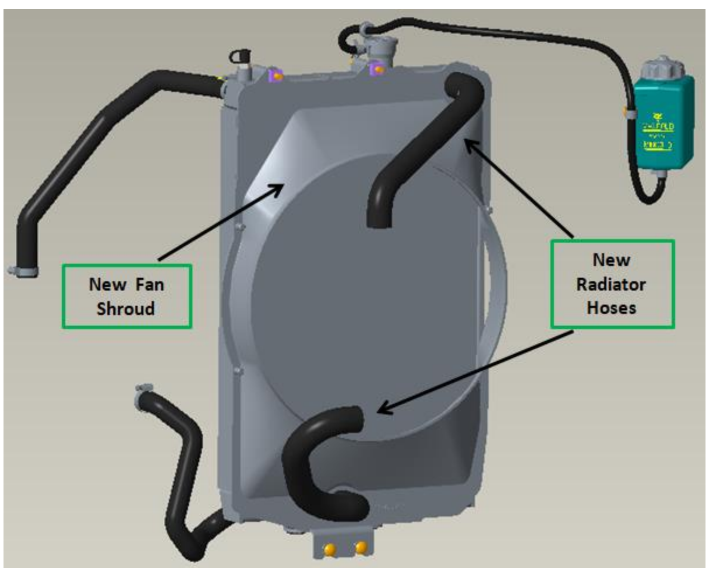


Figure 6 Proposal of new fan shroud and radiator hoses

2.5 Packaging proposal for the air intake system

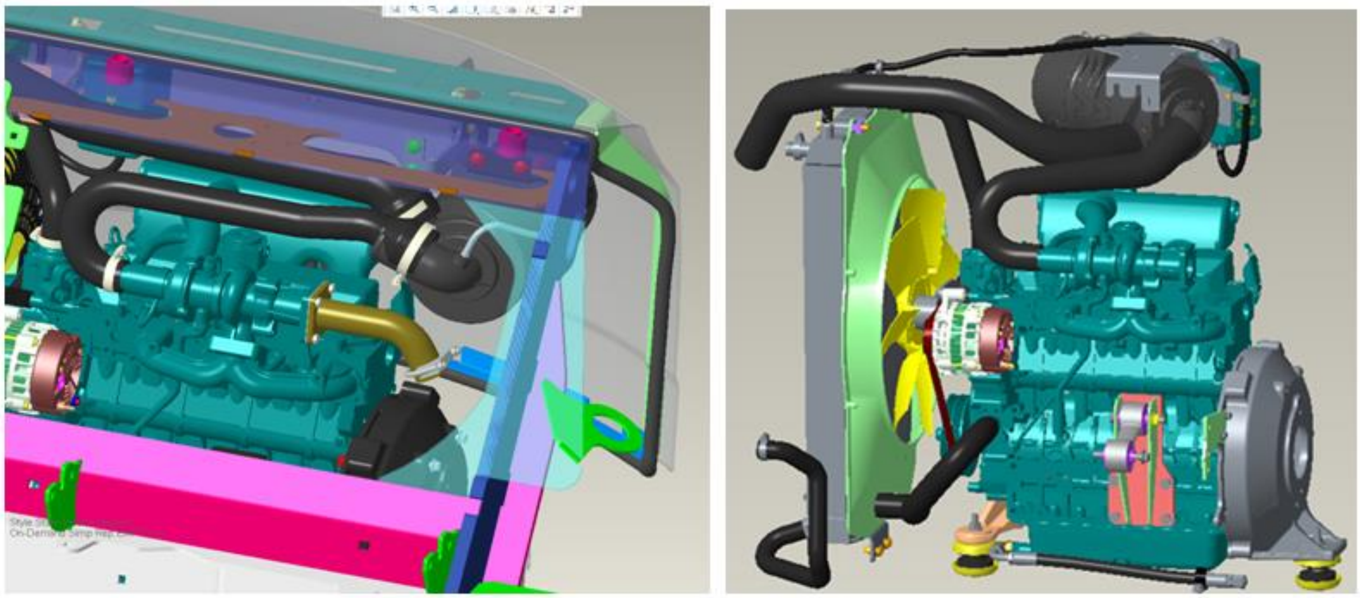


Figure 7 Air filter location in machine 2 (left image) and in new machine (right image)

The position of air filter and its hoses of machine 2 (shown in the left image of figure 7) was different as compared to the required position for the new machine. This position need to change because this air filter was in collision with the shock absorber of the tail gate of machine 1.

Therefore, the proposed and feasible solution (shown in the right image of figure 7) is to keep the new air filter at the same position of machine1.In this way, the other related components need not to be positioned in other places and need not to be modified. And therefore, the only modification was to design a new air filter and its air hoses.

For the new machine, proposal of air intake system and selection of proper air filter, and design of its air hoses are further elaborated in the next chapter 3.

3 Proposal of air intake system and selection of proper air filter, and design of its air hoses

3.1 Air intake system

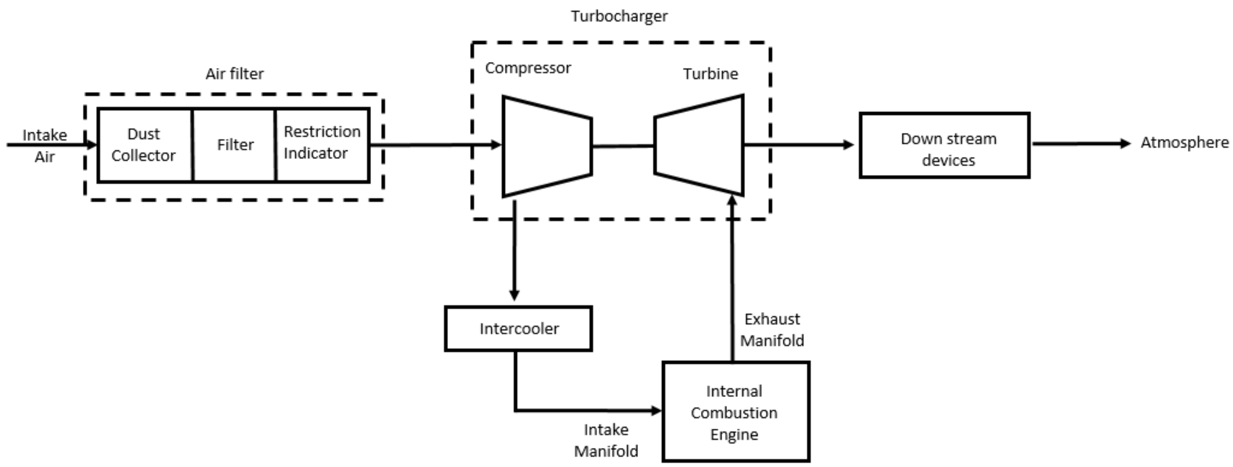


Figure 8 Flow diagram for an air intake system

The main function of an air intake system is to draw atmospheric air and send it to the combustion chamber of an engine via air filter, compressor of turbocharger, intercooler and intake manifold. Atmospheric air has oxygen that helps for better combustion in the engine. More and clean air in the combustion chamber means more power, better acceleration and lesser exhaust emissions.

The excavators are normally propelled by diesel engines and the above figure 8, shows that the intake hose of the air filter draws the atmospheric air, it gets filtered into the air filter and clean air gets sucked in to the compressor of the Turbocharger. This compressed and hot air gets cooled down in the intercooler and passes into the intake manifold. Then, from here it moves into the combustion chamber at the time of intake stroke. After combustion, the exhaust gases move towards the turbine of the turbocharger and due to high pressure energy, turbine moves at very high velocity and it leads to move the compressor. And the entire process repeats.

As we go further in this chapter, we will see proposed CAD model, selection of suitable air filter and the design of its hoses.

3.1.1 Proposed CAD model of the air intake system

As discussed in the motivation chapter that the engine and its accessories are used from machine 2 are positioned in the machine 1. As the modification of the upper structure of machine 1 would cause complexity thus decided to position the engine of machine 2 on some important parameters such as the required immersion of fan and shroud, no collision policy and keeping minimum distance of 25mm from all engine's surrounded parts, to avoid parts from collision during engine vibration during running condition.

For the new air filter, it was decided that it has to be placed exactly in the same location as that of the machine 1's air filter location. Therefore, the location of most of the parts related to old air filter will not be affected. And later, designing and routing of the hoses that transport air to intake manifold via air filter and compressor of turbocharger has performed.

Designing of these hoses has done with keeping in mind that the pressure loss should be under given permissible limit and routing has done to avoid collision, with keeping 25mm distance from all its surrounding parts and to use minimum possible hose length for minimizing the hose cost and to avoid the vibration during the running condition of the engine.

For more clear explanation, the image of the proposed CAD model of air intake system with the air flow direction is shown in figure 9.

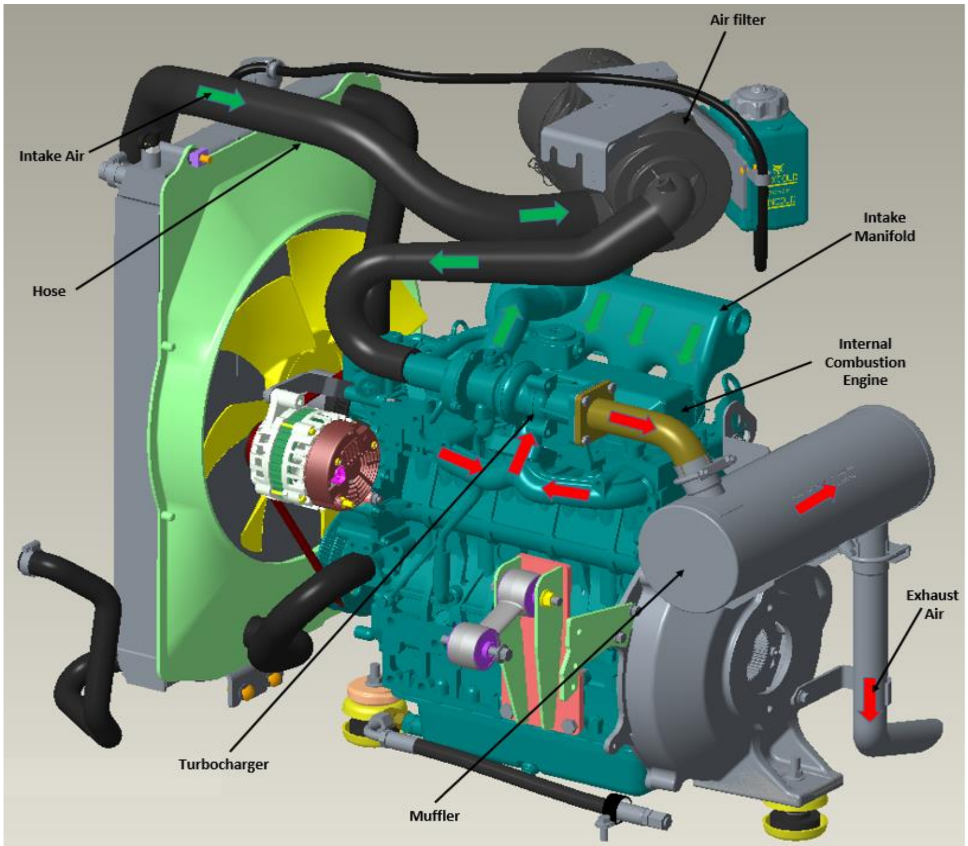


Figure 9 Proposed CAD model of air intake system

3.2 Air filter

Air filter prevents the harmful particles such as dirt, dust, pollen, pollutants etc. to enter in the intake manifold, engine and other components.

Damaged, blocked or aged filter will lead to decrease in engine performance, poor fuel economy, higher emissions, reduction in engine power, poor acceleration etc.

It is recommended to replace filters (primary and secondary) at regular intervals as per the OEM manual guidelines for the specific vehicle to avoid the above-mentioned problems.

For more clear explanation, the required air filter exploded view is shown in figure 10.

It is mainly made of three parts, which are given below:

1) Dust cover: It is used for dust collection and filter service.
2) Filter: It consists of primary and secondary filters. Secondary filter is inside the primary one. Primary is used to filter the rough particles and secondary for the fine particles. Filter housing has inlet port for incoming air via air inlet hose.
3) Outlet section: It should rotate and positioned as per the OEM requirement and glued together with the air filter housing. It has outlet port that connects to compressor of turbocharger via outlet air hose.

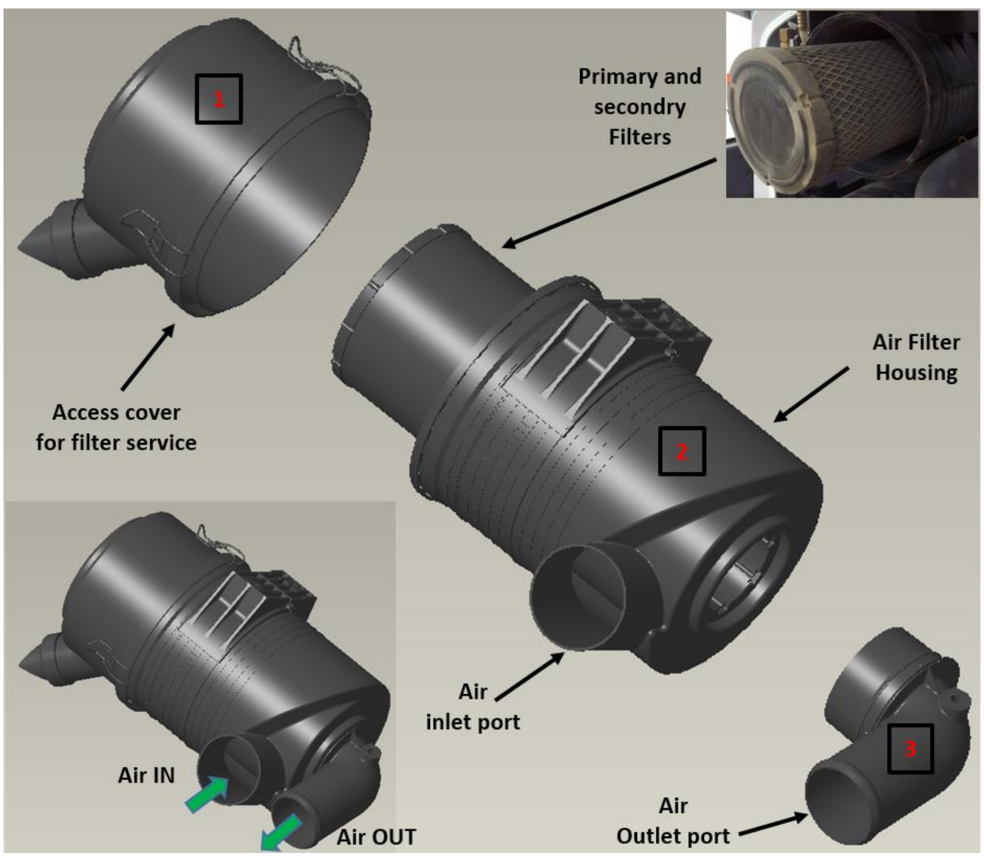


Figure 10 Exploded view of a required air filter

3.2.1 Selection of suitable air filter through performance curve and flow restriction calculation

While selecting the air filter we have to consider two important factors :

1) Required intake airflow for the engine.
2) Enviroment in which the air filter has to operate.

The ideal and the most accurate way to find the engine intake airflow is to take the specified data given by the engine manufacturer.[1]

There is an alternative method to get airflow for two stroke and four stroke engines which is shown below in table 2.

4 - Stroke Engine Formula	2 - Stroke Engine Formula
Airflow (m^3/min) = (Engine size (l) x rpm x VE)/2000	**Airflow (m^3/min) = (Engine size (l) x rpm x VE)/1000**
Where,	Where,
VE=Volumetric efficiency	**VE=Volumetric efficiency**
0.9 for Naturally aspirated gas engine	
0.9 for Naturally aspirated diesel engine	0.9 for Naturally aspirated diesel engine
1.6 for turbocharged diesel engine	1.4 for scavenge blower diesel engine
1.85 for turbocharged after cooled diesel engine	1.9 for turbocharged diesel engine

Table 2 Alternative method for intake air flow calculation [1]

Once we get to know the required airflow and the environment in which our filter will operate, we can see the air filter manufacture's manual to get the different vehicle vs airflow indication chart. An example of such chart from an air filter supplier has shown below in figure 11. [1]

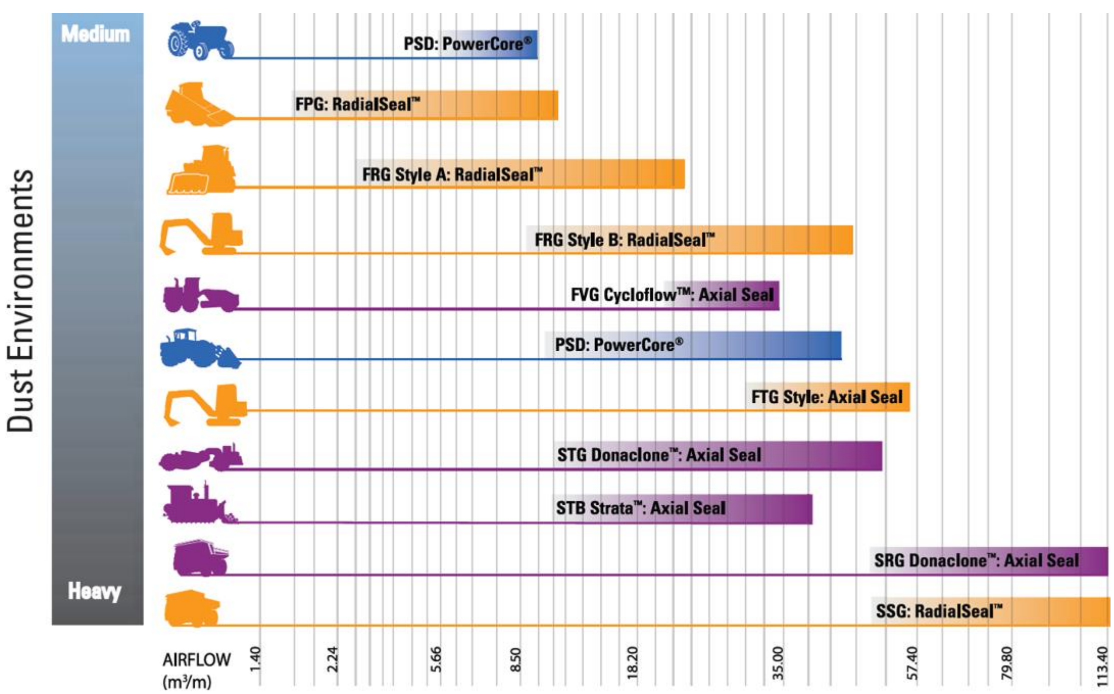


Figure 11 Dust environment vs airflow chart [1]

The engine manual normally has the airflow details. For an example, the engine requires 3.21 m^3/min of airflow and the machine is mini excavator therefore from the above figure 11, we can choose possible type of suitable air filter.

Every air filter due to its design and size has some flow restriction or pressure loss. Therefore, it requires discussion with the supplier and supplier will share the suitable air filter performance curve, an example is shown in figure 12. This performance curve shows relation between the flow restriction (on y axis) and airflow (on x axis). Check with the permissible limit and if the flow restriction is under limit, this air filter can be used. Also compare similar suitable filters based on other factors such as size, cost, reliability etc.

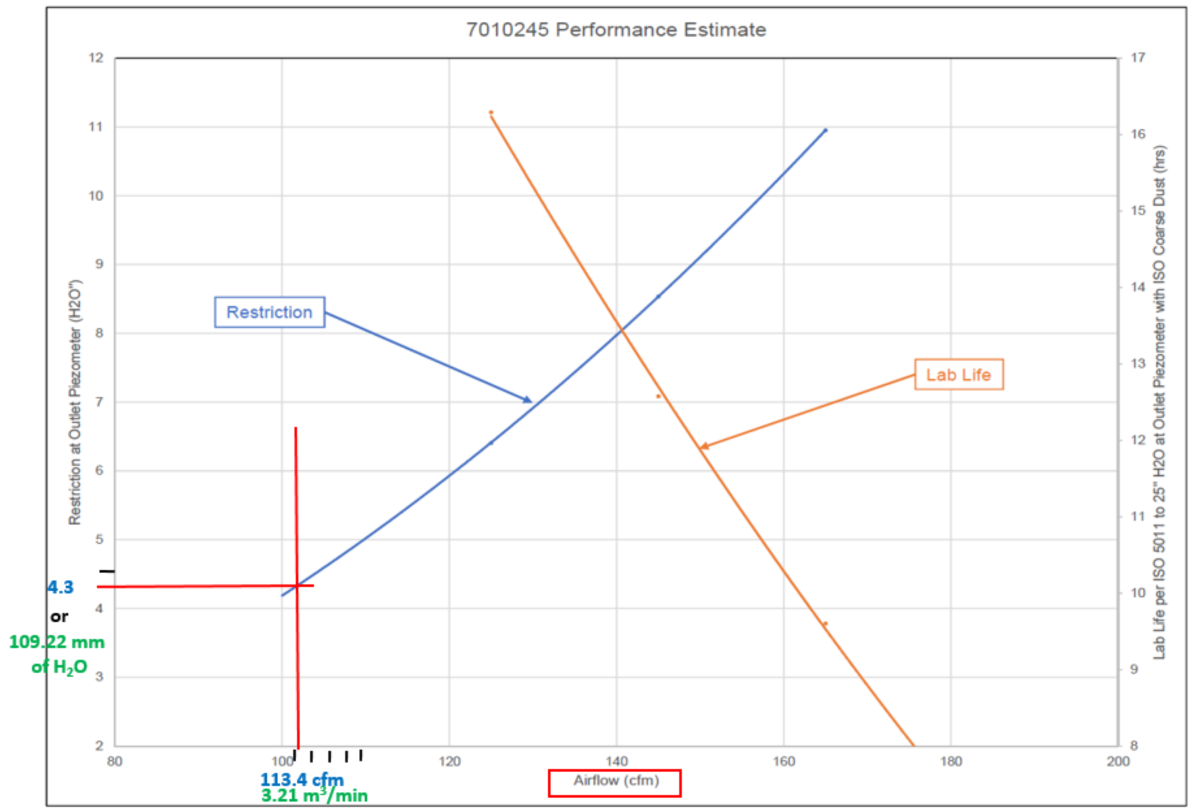


Figure 12 Performance curve for the required air filter

We can see from the figure 12 and table 3 that the air filter flow restriction is under limit.

Air filter			Units	Conclusion
1	Airflow or Volume flow rate	3.21	m^3/min	From Engine manual
2	Flow Restriction	109.22	mm of H_20	Under Limit
		1071.04	Pa	
	Flow Restriction Limit	250	mm of H_20	Max. limit
		2451.66	Pa	

Table 3 Conclusion of flow restriction with respect to the performance curve

3.3 Design consideration, calculation and CAD modeling in CREO for the air filter hoses

3.3.1 Design consideration and calculation for hoses

For the designing of any hose, some important steps need to follow which are given below:

1) First, we should know the application of the hose. Different type of hoses is used for different appliances such as radiator hoses, charge air cooler hoses, hydraulic system hoses, air filter hoses etc.
2) Then we should know some other important parameters such as bearable temperature and pressure of hose. Thus, we can decide the hose material and maximum possible hose length, as increase in length causes loss in pressure. [2]
3) Hose should have minimum number of bends and should avoid very sharp bends (follow the guidelines mentioned in table 4)
4) Now we should calculate the minimum possible bend radius (R) for curved and straight hoses with the help of hose supplier guidelines.
   The various bends such as normal, back to back and blended internal diameter transition are shown in the below figure 13. [2]

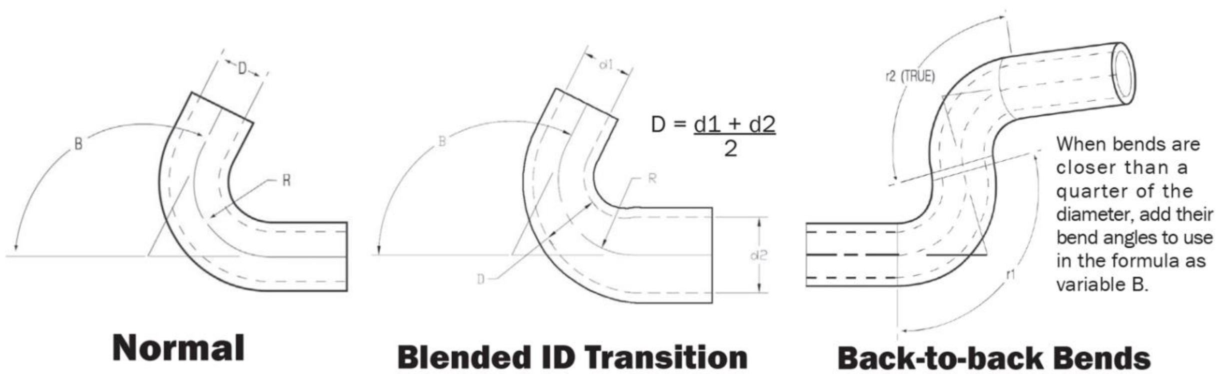


Figure 13 Types of hose bends [2]

As discussed above, for different application, we should use different type of hoses. Similarly, for different application we have different minimum possible bending radius.

<u>For curved hose</u>

1) For radiator hoses, it should be checked for 90 degrees bend angle (B) with 32.9 mm inner diameter (ID). By using design guidelines 32.9 mm has calculated the minimum possible bend radius (R) as shown in table 4.
2) For air intake hoses, it should be checked for 90 degrees bend angle (B) with 50 mm inner diameter (ID). By using design guidelines 37.5 mm has calculated the minimum possible bend radius (R) as shown in table 4.

<u>For straight hose</u>

1) For radiator hoses, it should be checked for 42.9 mm of outer diameter (OD). By using design guidelines 429 mm has calculated the minimum possible bend radius (R) as shown in below table 4.

Minimum Bend Radius Guidelines

Design limit for Curved Hose (R)			
For Radiator and Heater hoses	B (deg)	ID (mm)	R (mm)
	90	32.9	32.9
For Fuel and Oil hoses	B (deg)	ID (mm)	R (mm)
			0
For Air intake hoses	B (deg)	ID (mm)	R (mm)
	90	50	37.5
For Turbo air hoses	B (deg)	ID (mm)	R (mm)
			0

Design limit for Straight Hose (R)			
For Radiator, and Heater hoses		OD (mm)	R (mm)
		42.9	429
For Fuel and Oil hoses		OD (mm)	R (mm)
			0
For Wire Reinforced hoses		OD (mm)	R (mm)
			0

Curved Hose

For radiator, and heater hoses:
R = [(B ÷ 180) + .5] x D

For fuel and oil hoses:
R = [(B ÷ 180) + .5] x D x 1.25

For air intake hoses:
R = [(B ÷ 360) + .5] x D

For turbo air hoses:
R = [(B ÷ 180) + .5] x D x 2

B = Bend angle in degrees
R = Minimum centerline bend radius
D = Inside diameter of hose

Straight Hose

For radiator, and heater hoses:
R = 10 x Hose OD

For fuel and oil hoses:
R = 7 x Hose OD

For wire reinforced hoses*:
R = 4 x Hose OD
*Call Gates for hoses > 3" ID
or specific hose types

Table 4 Minimum bend radius guidelines [2]

3.3.2 CAD modeling of hose in CREO software

After design calculation, CAD modeling through piping module of CREO software need to complete. Below figure 14, shows the CAD view of the required hose routing.

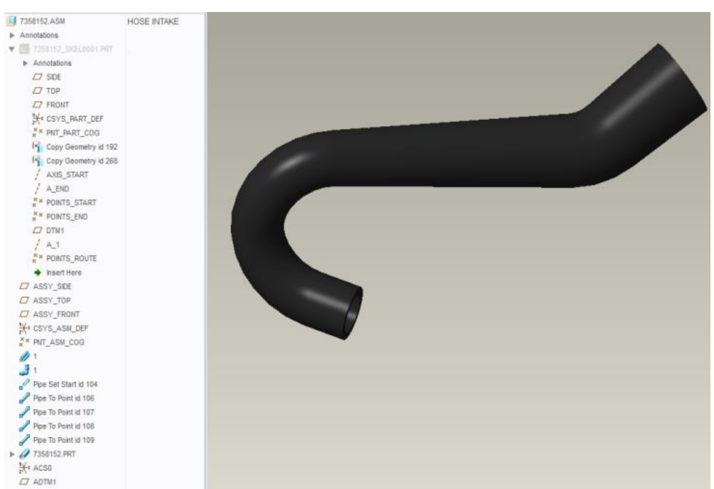


Figure 14 CAD modeling of air filter hose through CREO software

4 Air intake system and the cooling system - pressure drop calculation

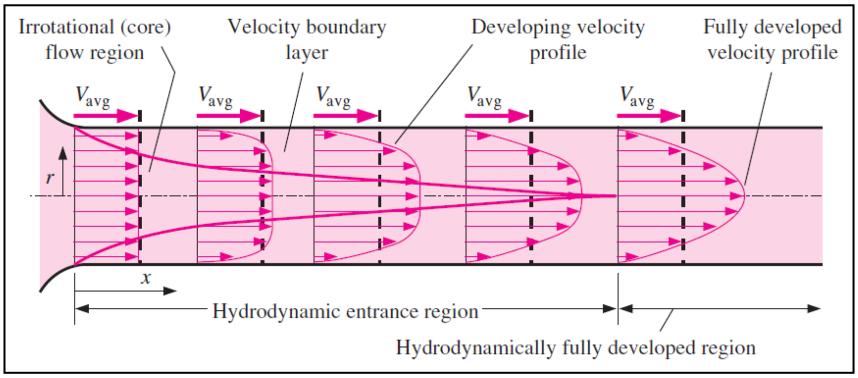


Figure 15 Development of velocity profile of the boundary layer in circular pipes and hoses [9]

[9] Flow of fluid in the circular pipe or hose causes drop in pressure due to friction between fluid particles and pipe surface. And adjacent fluid layers also cause friction with themselves leads to loss in pressure.

Figure 15 shows the development of velocity profile from the entrance region of pipe until it becomes fully developed velocity profile. At the entrance of a pipe, where viscous shearing forces come in to act due to fluid viscosity, this region is called velocity boundary layer. Before this region, where the velocity remain almost constant as frictional effects are negligible is called irrotational flow region. Up to the region, where velocity profile will become constant is called hydrodynamic entrance region. Till this region velocity profile develops and gradually increases the boundary layer thickness. When the velocity profile and wall shear stress will become constant, this region is called hydrodynamic fully developed region shown in below figure 16.

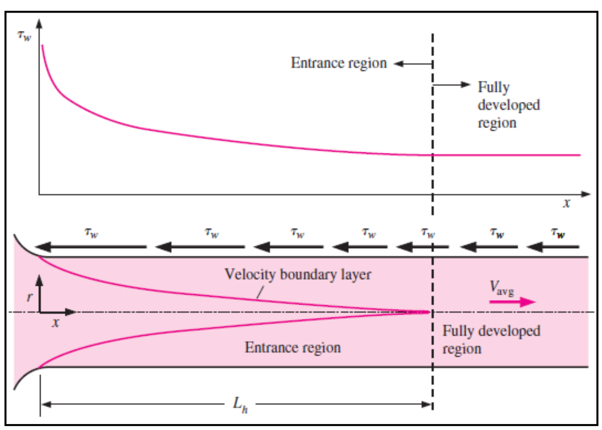


Figure 16 Wall shear stress profile variation during the fluid flow [9]

We can see that wall shear stress is max at the hose inlet and gradually decreases and becomes constant at fully developed region. Thus, the pressure drop is maximum at the entrance region and due to this region average friction factor increases for the entire hose or pipe. Friction factor is significant for the shorter pipes and negligible for the longer pipes.

4.1 Pressure loss calculation in circular pipes and hoses with air as a medium [3] [5] [6] [7] [8]

Pressure loss ($\boldsymbol{dP}$) in the air hoses has calculated using the **Darcy weisbach equation** (4.1).

$$\boldsymbol{dP = \lambda \frac{\rho_{air}}{2} \frac{l}{d} w_{mean}^2} \tag{4.1}$$

Where friction factor λ for the circular pipes and hoses are,

$$\lambda = \frac{64}{Re} \qquad If \quad Re < 2300 \;\; for\ laminar\ flow \tag{4.2}$$

$$\lambda = \lambda_{2300} + \frac{\lambda_{4000} - \lambda_{2300}}{4000 - 2300}(Re - 2300) \qquad If \;\; 2300 \le Re \le 4000\ for\ trans\ flow \tag{4.3}$$

$$\frac{1}{\sqrt{\lambda}} = -2\,log_{10}\left[\frac{2.51}{Re\sqrt{\lambda}} + \frac{k}{3.71d}\right] \qquad If \;\; Re > 4000\ for\ turbulent\ flow \tag{4.4}$$

Where,

$$Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{w_{mean}d}{\nu_{air}} \tag{4.5}$$

$$w_{mean} = \frac{\dot{m}}{\rho_{air}\,A} \tag{4.6}$$

$$\nu_{air} = \frac{\mu_{air}}{\rho_{air}} \tag{4.7}$$

$$\mu_{air} = \frac{1.458 \times 10^{-6}(t + 273.15)^{1\cdot 5}}{(t + 273 \cdot 15) + 110.4} \tag{4.8}$$

$$\rho_{air} = \frac{(((P - P_v) \times 0.028964) + (P_v \times 0.018016))}{[8.314t + 273.15]} \tag{4.9}$$

$$P_v = \phi\left(6 \cdot 1078 \times 10^{\left(\frac{7.5t}{t+237.3}\right)}\right) \tag{4.10}$$

Specially for the bend sections, the below formula for the pressure loss has used.[4] [8]

$$dP = \lambda C_\alpha \frac{\rho_{air}}{2}\left(\frac{l}{d}\right)_{eq} w_{mean}^2 \tag{4.11}$$

$$\left(\frac{l}{d}\right)_{eq} = 40 - 15\left(\frac{r}{d}\right) \quad If\,\frac{r}{d} \leq 2 \tag{4.12}$$

$$\left(\frac{l}{d}\right)_{eq} = 5 + 2 \cdot 5\left(\frac{r}{d}\right) \quad If\,\frac{r}{d} > 2 \tag{4.13}$$

$$C_{\alpha} = \left(\frac{\alpha}{90}\right)^{0.75} \tag{4.14}$$

Symbols and units

dP……………Pressure loss (Pa)

λ……............... Friction coefficient (unit less)

ρ_{air} ....Density of air (kg/m^3)

l………………. Length of straight pipe or hose section (m)

d……………..... Inner hose diameter (m)

w_{mean}…………Mean velocity (m/s)

Re…………..… Reynolds number (unit less)

k……………..... Absolute surface roughness (m)

$\dot{m}$……………..... Mass flow rate (kg/sec)

A……………..... Cross sectional area (m^2)

μ_{air}……………. Dynamic viscosity of air (Ns/m^2)

ν_{air}……………. Kinematic viscosity of air (m^2/s)

P……………..... Absolute pressure (Pa)

P_v……………..... Partial vapour pressure (Pa)

ϕ……………..... Relative humidity (%)

t……………...... Temperature (K)

C_{α}……………..... Correction factor (unit less)

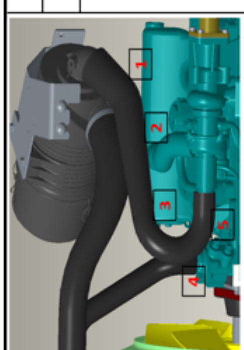
$\left(\frac{l}{d}\right)_{eq}$……………Equivalent length (unit less)

r……………...... Bending radius (m)

α……………......Bending angle (degree)

The above given standard formulae were used to calculate the pressure loss in the air filter hose in excel, which can be seen in the figure 17.

Green color shows the inputs and the orange shows the outputs and finally the pressure loss in yellow. Benefit of this calculation helps to design the air hoses with pressure loss under permissible limit. If in case, the pressure loss exceeds the permissible limit then number of hose bend and hose length need to reduce as the pressure loss is directly dependent on them. And later after CAD modelling, the hose drawings need to send to the respective supplier for the manufacturing.



Input	Output
(green)	(orange)

Pressure Loss Calculation_Airfilter Hose

SN	Circular Pipes/Hoses	Medium	Length (m)	Inner Dia (m)	Bend Radius (m)	Bend Angle (deg)	Bend Radius to Dia Ratio	Absolute Roughness (m)	Temprature (°C)	Absolute Pressure (Pa)	Relative humidity	Mass flow rate (kg/hr)
			l	d	r	α	r/d	k	t	P	Φ	ṁ
1	Bent section	AIR	NA	0.062	0.065	35	1.0483871	0.00003	43	101325	0.5	215
2	Straight section	AIR	0.228	0.05	NA	NA	NA	0.00003	43	101325	0.5	215
3	Bent section	AIR	NA	0.0371	0.065	90	1.7520216	0.00003	43	101325	0.5	215
4	Bent section	AIR	NA	0.0371	0.065	90	1.7520216	0.00003	43	101325	0.5	215
5	Straight section	AIR	0.011	0.0371	NA	NA	NA	0.00003	43	101325	0.5	215

Hose Cross section Area (m^2)	Equivalent Length	Correction Factor	Velocity (m/s)	Partial vapour pressure (Pa)	Air Density (kg/m^3)	Dynamic viscosity (Ns/m^2)	Kinematic viscosity (m^2/s)	Reynolds Number	Laminar or Turbulent	Turbulent: Friction Factor	Turbulent: Pressure Loss (Pa)
A	$(l/d)_{eq}$	C_{α}	w	P_v	ρ_{air}	μ_{air}	ν_{air}	Re		λ	dP
0.003019	24.2741935	0.4924579	17.7199	43.192445	1.116354077	1.9214E-05	1.7212E-05	63830.375	Turbulent	0.02162262	45.30190768
0.001963	NA	NA	27.2461	43.192445	1.116354077	1.9214E-05	1.7212E-05	79149.665	Turbulent	0.02135339	40.34712469
0.001081	13.7196765	1	49.4876	43.192445	1.116354077	1.9214E-05	1.7212E-05	106670.71	Turbulent	0.02135669	400.5374659
0.001081	13.7196765	1	49.4876	43.192445	1.116354077	1.9214E-05	1.7212E-05	106670.71	Turbulent	0.02135669	400.5374659
0.001081	NA	NA	49.4876	43.192445	1.116354077	1.9214E-05	1.7212E-05	106670.71	Turbulent	0.02135669	8.656015962
										Total P drop (Pa)	895.38

Figure 17 Pressure loss calculation of air filter hose

4.2 Pressure loss calculation in circular pipes and hoses with water as a medium [3] [8]

Using the equation (4.1), pressure loss ($\boldsymbol{dP}$) in the water hoses can also be calculated as below:

$$\boldsymbol{dP = \lambda \frac{\rho_{water}}{2} \frac{l}{d} w_{mean}^2}$$

Using the same equations (4.2), (4.3), and (4.4), similarly we have friction factor λ for the circular pipes and hoses as,

$$\lambda = \frac{64}{Re} \qquad If \quad Re < 2300 \;\; for\ laminar\ flow$$

$$\lambda = \lambda_{2300} + \frac{\lambda_{4000} - \lambda_{2300}}{4000 - 2300}(Re - 2300) \qquad If \;\; 2300 \leq Re \leq 4000\ for\ transitional\ flow$$

$$\frac{1}{\sqrt{\lambda}} = -2\, log_{10}\left[\frac{2.51}{Re\sqrt{\lambda}} + \frac{k}{3.71d}\right] \qquad If \;\; Re > 4000\ for\ turbulent\ flow$$

Using equations (4.5) and (4.6), we have equations for water

$$Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{w_{mean}d}{\nu_{water}}$$

$$w_{mean} = \frac{\dot{m}}{\rho_{water}\, A}$$

$$\nu_{water} = \frac{1 \cdot 79 \times 10^{-6}}{1 + 0.0337t + 0.000221t^2} \tag{4.15}$$

$$\rho_{water} = 1000 - (t - 4)[0.097 + 0.0036(t - 4)] \tag{4.16}$$

Using equations (4.11), (4.11), (4.11), and (4.11), the below formula for the pressure loss has used for the bend sections.[4] [8]

$$dP = \lambda C_\alpha \frac{\rho_{water}}{2}\left(\frac{l}{d}\right)_{eq} w_{mean}^2$$

$$\left(\frac{l}{d}\right)_{eq} = 40 - 15\left(\frac{r}{d}\right) \qquad If\, \frac{r}{d} \leq 2$$

$$\left(\frac{l}{d}\right)_{eq} = 5 + 2 \cdot 5\left(\frac{r}{d}\right) \qquad If\, \frac{r}{d} > 2$$

$$C_\alpha = \left(\frac{\alpha}{90}\right)^{0.75}$$

Symbols and Units

dP……………Pressure loss (Pa)

λ……............. Friction coefficient (unit less)

ρ_{water} ....Density of water (kg/m^3)

l………………. Length of straight pipe or hose section (m)

d……………..... Inner hose diameter (m)

w_{mean}…………Mean velocity (m/s)

Re…………..… Reynolds number (unit less)

k……………..... Absolute surface roughness (m)

$\dot{m}$……………..... Mass flow rate (kg/sec)

A……………..... Cross sectional area (m^2)

ν_{water}…………. Kinematic viscosity of water (m^2/s)

t……………...... Temperature (K)

C_α……………..... Correction factor (unit less)

$\left(\frac{l}{d}\right)_{eq}$……………Equivalent length (unit less)

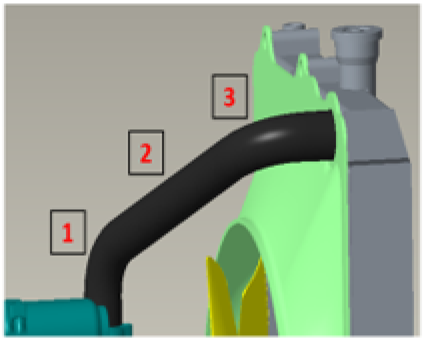
r……………....... Bending radius (m)

α……………......Bending angle (degree)

Using the above given standard formulae, calculation of the pressure loss in the radiator in and out hoses in excel can be seen in the figure 18 and in figure 19.

In these figures, the comparison between the excel calculated and KULI software pressure drop results has shown, with a maximum error of 6 % which is quite close.

Modelling of cooling system through KULI software takes time because of unavailability of technical data of radiator and oil cooler at initial stages. Benefit of this calculation helps to do the design of hoses under close approximation of pressure loss. Thus, helps in early design of hoses and its manufacturing thus saves a lot of time.



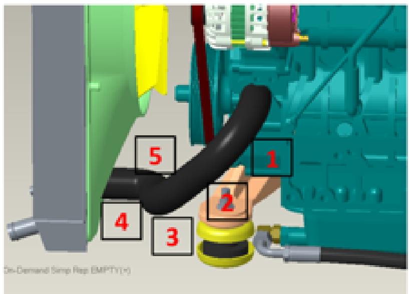
Input	Output

Pressure Loss Calculation_RAD IN Hose

SN	Circular Pipes/Hoses	Flow Medium	Length (m)	Inner Dia (m)	Bend Radius (m)	Bend Angle (deg)	Bend Radius to Dia Ratio	Absolute Roughness (m)	Temprature (°C)	Mass flow rate (kg/hr)
			l	d	r	α	r/d	k	t	ṁ
1	Bent section	WATER	NA	0.03298	0.06	65	1.819284415	0.00003	99	4464
2	Straight section	WATER	0.229	0.03298	NA	NA	NA	0.00003	99	4464
3	Bent section	WATER	NA	0.03698	0.08	65	2.163331531	0.00003	99	4464

Hose Cross section Area (m^2)	Equivalent Length	Correction Factor	Velocity (m/s)	Density (kg/m^3)	Kinematic Viscosity (m^2/s)	Reynolds Number	Laminar or Turbulent	Turbulent: Friction Factor	Turbulent: Pressure Loss (Pa)	KULI Comparison	% Error
A	$(l/d)_{eq}$	C_{α}	w	ρ_{water}	ν_{water}	Re		λ	dP	Pa	
0.00085426	12.710734	0.7834353	1.51472	958.295	2.7529E-07	181467.01	Turbulent	0.020797081	227.6714905	236.459086	3.7163
0.00085426	NA	NA	1.51472	958.295	2.7529E-07	181467.01	Turbulent	0.020797081	158.7521895	164.565602	3.5326
0.00107405	10.408329	0.7834353	1.20476	958.295	2.7529E-07	161838.34	Turbulent	0.020575558	116.6818342	122.737068	4.9335
								Total P drop (Pa)	503.1055		

Figure 18 Pressure loss calculation of radiator IN hose and comparison with KULI result



Input	
Output	

Pressure Loss Calculation_RAD OUT Hose

SN	Circular Pipes/Hoses	Flow Medium	Length (m)	Inner Dia (m)	Bend Radius (m)	Bend Angle (deg)	Bend Radius to Dia Ratio	Absolute Roughness (m)	Temprature (°C)	Mass flow rate (kg/hr)
			l	d	r	α	r/d	k	t	ṁ
1	Bent section	WATER	NA	0.03298	0.07	115	2.12249848	0.00003	93.6	4464
2	Straight section		0.065	0.03298	NA	NA	NA	0.00003	93.6	4464
3	Bent section		NA	0.03298	0.13	60	3.9417829	0.00003	93.6	4464
4	Straight section		0.007	0.03298	NA	NA	NA	0.00003	93.6	4464
5	Bent section		NA	0.03698	0.033	90	0.89237426	0.00003	93.6	4464

Hose Cross section Area (m^2)	Equivalent Length	Correction Factor	Velocity (m/s)	Density (kg/m^3)	Kinematic viscosity (m^2/s)	Reynolds Number	Laminar or Turbulent	Turbulent: Friction Factor	Turbulent: Pressure Loss (Pa)	KULI Comparison	% Error
A	$(l/d)_{eq}$	C_{α}	w	ρ_{water}	ν_{water}	Re		λ	dP	Pa	
0.00085426	10.306246	1.2018257	1.50825	962.4074	2.939E-07	169247.36	Turbulent	0.02089843	283.35335	296.25438	4.3547
0.00085426	NA	NA	1.50825	962.4074	2.939E-07	169247.36	Turbulent	0.02089843	45.086762	47.125692	4.3266
0.00085426	14.854457	0.7377879	1.50825	962.4074	2.939E-07	169247.36	Turbulent	0.02089843	250.71175	262.10301	4.3461
0.00085426	NA	NA	1.50825	962.4074	2.939E-07	169247.36	Turbulent	0.02089843	4.8554974	5.07508	4.3267
0.00107405	26.614386	1	1.19961	962.4074	2.939E-07	150940.46	Turbulent	0.02069208	381.35399	404.29835	5.6751
								Total P drop (Pa)	965.36		

Figure 19 Pressure loss calculation of radiator OUT hose and comparison with KULI result

Figure 20, concludes the pressure drop summary of the air filter and the radiator system.

Conclusion is that the total sum of pressure drop in air filter and its hose is under permissible limit.

Similarly, total sum of pressure drops in radiator, radiator tank and its hoses are under permissible limit too.

This analysis helps to in CAD modelling and design of hoses at very early stage.

PRESSURE DROP SUMMARY								
Sno	System	Flow Medium	Section	Pressure drop	Net Pressure drop	Net Pressure drop	Permmisible limit	Conclusion
				Pa	Pa	bar	bar	
1	Air Filter	Air	Air Filter	1071	1966.37998	0.0196638	0.02451663	Under Permissible Limit
			Air Filter_Hose	895.37998				
2	RAD	Water	RAD_IN hose	503.1055143	7108.466859	0.071084669	0.25	Under Permissible Limit
			RAD_Heat Exchanger	4700				
			RAD_Heat Exchanger_tank	940				
			RAD_OUT hose	965.3613449				

Figure 20 Pressure drop summary for the air filter and radiator system

5 Optimization of cooling system using KULI software and selection of suitable fan based on KULI results

5.1 Basic heat transfer theory

Heat transfer is the transition of thermal energy in three different mechanisms namely conduction, convection and radiation [10]. All these mechanisms occur in the cooling system. We will discuss them in brief in the following sections.

5.1.1 Conduction

''Conduction is the transfer of energy from high-energy particles of a substance to the adjacent low-energy particles because of interactions between the particles. In solids, conduction is the result of the vibrations of molecules and the energy transport by free electrons. The amount of energy transferred depends on the internal temperature difference in the volume, cross section area and thermal conductivity of the material. The heat transfer rate can be described by'' [11] :

$$Q_{Cond} = k \times A \times \frac{dT}{dx}$$

Where, Q_{Cond} is the rate of heat transfer, k is the thermal conductivity in (W/m-K), A is the cross-sectional area in (m^2), dT is the local temperature difference between the layers in (K) and dx is the distance between them in (m).

5.1.2 Convection

''Convection is the energy transfer between a solid surface and an adjacent fluid that is in motion; it is the combined effect of conduction and fluid motion. Convection can be natural or forced. Natural convection is a form of conduction between the volume and the stationary fluid and occurs because of the density differences due to temperature change in the fluid. Natural convection can be described by'' [11]:

$$Q_{Conv} = h \times A_s \times (T - T_\infty)$$

Where, Q_{Conv} is the rate of heat transfer, h is the convection heat transfer coefficient in (W/m2-K), T is the surface temperature in (K) and T_∞ is the fluid temperature (K) outside the thermal boundary layer.

Convection and conduction both need medium for their heat transfer mechanism. It occurs by means of the molecules movement within fluids. In the cooling system, the convective heat transfer occurs in the pipes and hoses when there is a difference in temperature between the pipe wall and the coolant flowing inside the pipe. In this case, the fluid creates a thermal boundary layer. Near the pipe surface, the fluid velocity is less and when moving towards the center the fluid velocity reaches maximum.

5.1.3 Radiation

‘’All bodies with a temperature above absolute zero emit thermal radiation. The energy emitted is in the form of electromagnetic waves and transfers heat from the volume to the surrounding environment. Radiation depends on the surface area of the volume, the temperature difference between the volume and the surrounding environment and the emissivity of the material. The emissivity is a measure of how close the material is to an ideal surface in terms of a maximum radiation rate. The net heat transferred by radiation can be described by’’ [11]

$$Q_{rad} = \varepsilon \times \sigma \times A_s \times (T^4 - T_\infty^4)$$

Where, Q_{rad} is the net radiation heat transfer rate, ε is the emissivity (a dimensionless number) , σ is the Stefan-Boltzmann constant which is 5.6704×10^{-8} in (W/m^2-K^4), A_s is the surface area in (m^2), T is the surface temperature in (K) and T_∞ is the temperature of surroundings in (K).

5.2 Cooling system of a mini excavator

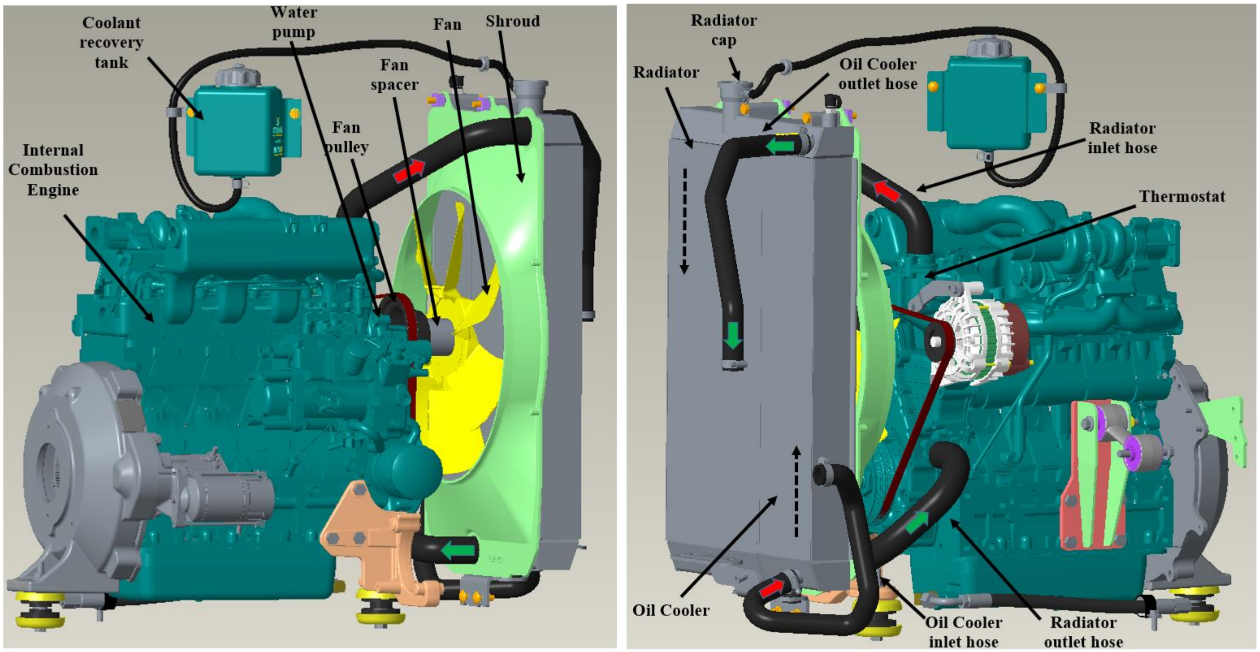


Figure 21 Cooling system of a mini excavator

Figure 21, shows the proposed CAD model for the cooling system. It has various components which are briefly described in the later chapters. In CAD modeling, engine was first placed in the correct location then decided to design the new fan shroud as it saves the modification in the front mount (shown in light orange colour, in figure 21) thus saves lot of money and time. But proper designing of fan shroud is must therefore requires proper CFD analysis because it affects the air flow efficiency.

Later designing of water hoses for radiator has done under the permissible limits. Location of inlet and outlet for the radiator hoses has decided as per the flow of the water in the radiator. As in this case, water flows from top to bottom, inlet and outlet has to be diagonally apart from each other for the maximum cooling performance.

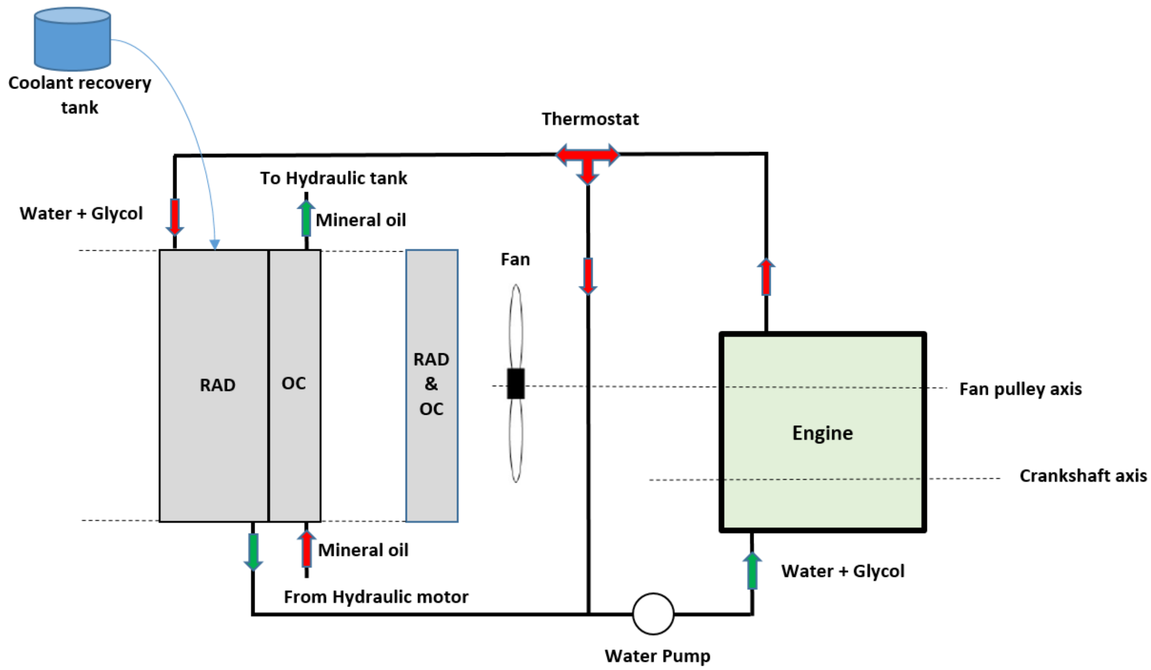


Figure 22 Schematic of the radiator and the oil cooler circuit

5.2.1 Engine radiator

Radiator is the heat exchanger that helps to cool the internal combustion engine of automobile, railway locomotives etc. There are two types of motor vehicle radiator:

1) Fin or tube type
2) Corrugated fin type

Both can be used as downdraft (flow from top to bottom) and cross-flow (horizontal flow). Fin and tube type radiator is used here, where fins are surrounded on tubes, they can be flat or slightly corrugated and tubes can be round, flat or oval. They are connected by soldering or by expanding the tubes. They have well resistant to compression and insensitive to vibration. The used radiator is an air-to-liquid with downdraft type. For the location of the radiator, refer figure 21.

Factors that will affect the size and effectiveness of a radiator are:

1) Increase in coolant flow rate reduces the temperature drop in between entry and exit passages.
2) Increase in coolant flow rate raises the power required to drive the water pump and thus reduces the efficiency at high flow rates.
3) Increase in temperature difference between the inner coolant and outside air of radiator raises the heat dissipation capacity.

4) Coolant as water with 50% ethylene glycol reduces the heat dissipation capacity by about 15% due to the lower specific heat capacity as compared to 100% water.

5.2.2 Hydraulic oil cooler

Excess heat is dangerous for hydraulic systems. Hydraulic oil cooler removes excess heat generated due to energy losses in a system to the surrounding environment. Therefore, it is widely used for agricultural, mobile, manufacturing, and industrial purposes. For the location of the hydraulic oil cooler, refer figure 21.

Hydraulic oil coolers are often essential for designing temperature optimized hydraulic systems that keep oil temperatures within a limited range. It helps in cost efficient operation, better performance, and less harmful to environmental. Important points for the hydraulic cooler oil that need to follow are:

1) Maintaining the right temperature keeps oil at its required viscosity, thus mechanical components are sufficiently lubricated and hydraulic components run at highest efficiency. Otherwise, higher temperature can reduce the life of components, causes oil leakage, increases problem of cavitation, and finally damage the components.
2) Excess heat also degrades the hydraulic oil, form harmful substances on component surfaces, and deteriorate rubber and elastomeric seals.
3) This lead to less maintenance, fewer shutdowns, and reduces service time and repair costs.

5.2.3 Thermostat

When the engine is at cold or warming up state, thermostats are used to block the coolant circulation in and from the radiator so that the coolant absorbs and accumulates the rejected combustion heat and helps the engine to reach its working temperature quickly. When the coolant reaches the valve opening temperature of the thermostat, the valve starts to open and the coolant flows in the radiator. It opens full, only at the designed operating temperature. The valve is activated by temperature sensitive wax. Wax is filled in a capsule which has rod connected to the valve. When temperature reaches up to certain limit it starts to melt, and the rod pushes down due to gravity causing opening of the valve. And then coolant flows towards the radiator through coolant hose. Thermostat also improves the engine and radiator performance. For the location of the thermostat, refer figure 21.

5.2.4 Coolant pump

Coolant pump or water pump is the simple centrifugal pump which is driven mechanically by engine either by gear drive or by belt drive. As the belt drive transmission have higher efficiency thus used by most of the manufacturers. The pump uses centrifugal force to push the engine coolant outwards towards the engine block and cylinder head. Here engine coolant absorbs the heat and at specified temperature limit, it goes to radiator. In radiator, engine coolant cools down and returns to the pump and hits the pump vanes thus enter the engine again. For the location of the water pump, refer figure 21.

5.2.5 Engine coolant

The engine coolant usually consists of the water mixed with ethylene glycol in a 50/50 ratio approximately. We know water boils at 100°C and freezes at 0°C. In winter, when the temperature goes below 0°C, water freezes and expands its volume around 9 percent can cause crack in the engine parts and radiator or lead to other damages. By adding ethylene glycol, we can reduce its freezing point and thus also improve corrosion resistance. It also raises the boiling point of the coolant that is important for the hot day conditions, when the higher temperature difference between air and coolant is desirable as it improves the heat transfer performance of the radiator.

5.2.6 Air conditioning unit

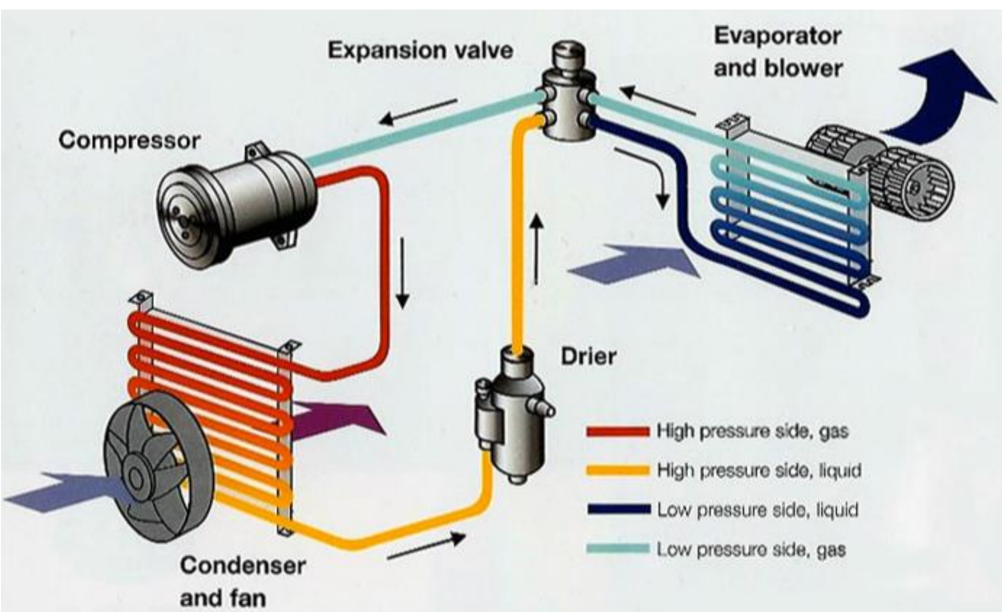


Figure 23 Air conditioning flow diagram [12]

Air conditioning has two main purposes to cool down and removes the moisture from the air in the passenger cabin thus to feel comfortable for the driver and passengers. After year 1996, non-chlorofluorocarbons, R-134A is used as refrigerants which is safe for the environment.

Air conditioning unit has several components as shown in figure 23, which have following functions:

1) Compressor: It compresses low pressure refrigerant (vapour state) that comes from expansion valve cause increase in pressure and this high-pressure vapours moves to condenser.
2) Condenser and fan: It is mounted in front of the engine's radiator. As forced air flows through it due to fan, causes drop in temperature thus refrigerant condenses from high pressure vapour that comes from compressor into high-pressure liquid.
3) Drier: It receives the incoming high-pressure liquid and dries out any moisture that may have leaked into the refrigerant. Otherwise, moisture in the system may lead to creation of ice crystals that cause blockages and mechanical damage to the components.
4) Expansion valve: The high-pressure liquid flows from the drier to the expansion valve. Here the pressurized liquid expands and becomes low pressure cold vaporizing liquid spray.
5) Evaporator and blower: It looks like a radiator and is usually mounted inside the passenger cabin. As the cold low-pressure refrigerant is passed into the evaporator, it vaporizes and absorbs the heat from the air of the passenger cabin. The blower fan blows the air outside of the evaporator, so cold air is circulated inside the cabin. On the 'air-side' of the evaporator, the moisture in the air is reduced. And then the compressor sucks the low pressure vapour and the whole cycle starts again.

5.2.7 Cooling fan

The radiator performance is highly affected by the amount of air going through it. A fan is used for sucking the air in and therefore increasing this amount of air. The fan is usually mechanically connected to the engine shaft through belt drive mechanism and its speed is directly dependent on the engine RPM.A viscous clutch along with fan can also be used, it allows to decrease the rotational speed when extra air flow is not needed.

5.2.8 Fan shroud

A fan shroud is used around cooling fan on heat exchanger side to increase the air flow efficiency. Thus, it should be properly designed so that there will be minimum air resistance and should be checked through proper CFD analysis. For the location of the fan shroud, refer figure 21.

5.2.9 Pipes and hoses

Pipes and hoses are used to connect different components and transport their respective coolant to the various parts of the cooling system thus they must be designed to withstand high temperatures, pressures and mechanical vibrations. As it creates loss in pressure, thus also must be designed under permissible limits. For the location of the hoses, refer figure 21.

5.3 KULI – Thermal energy management software

5.3.1 Overview

In today's automotive industry, optimal and efficient use of energy at any operating point of the vehicle is most important. Thus, the engineers are mainly focus on the powertrain system, heating and air conditioning, and engine cooling to ensure safe and efficient operation. KULI helps in simulation and optimization in the thermal management system. KULI effectively support the engineer in setting up system components and control strategies with the aim to optimize performance, comfort and operating reliability of the vehicle. It also provides quick analysis and solution without expensive prototype building and bench tests. [14]

5.3.2 Purpose

"During the concept phase engineers must consider different engines, gearboxes, heat exchangers, fans, carry-over parts, batteries etc. as well as control elements and actuators.

A general issue for state of the art vehicle developments is the dimensioning of the cooling system to guarantee the required performance and emission levels. KULI simulation software generates and optimizes the thermal management system meeting all requirements on component-, system- and vehicle level. KULI assists on specifying and validating OEM requirements right from the start such as legal compliance, standards and regulations". [14]

5.3.3 Modules

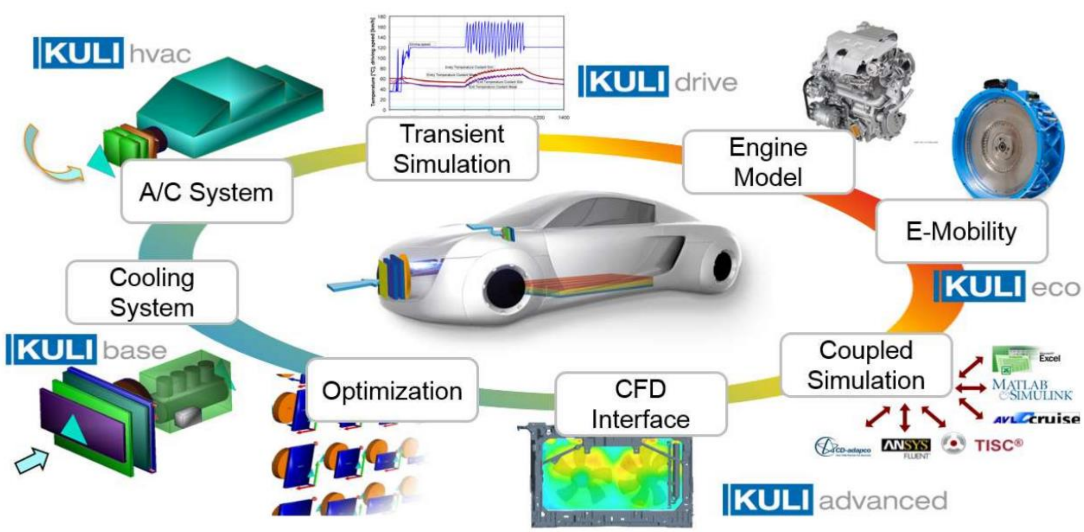


Figure 24 KULI modular structure [13]

KULI modular structure is very flexible and multipurpose thus helps the user to effectively perform the various simulation task.

Different KULI modules are available for each application such as:

1) Steady state vs. transient or driving cycle calculation
2) Engine cooling systems and integration of AC or HVAC systems
3) 1D simulation and integration of 3D airflow distribution
4) Working with automatic optimization routines
5) What-if scenarios

The built-in postprocessor enables the possibility to analyze the results in detail. An export function to Microsoft Office Excel allows the user to work in a standardized environment. [14]

5.3.4 Benefits

Thermal management has a high potential for improving fuel economy, reducing emissions and increase efficiency of conventional, hybrid and electric vehicles [14]. It also provides

1) Efficient and quick analysis of cooling, HVAC, and drivetrain systems.
2) Enormous cost and time reduction at variation and optimization of systems compared to test bench.
3) Due to its modular structure KULI is multipurpose tool, shown in figure 24.
4) Software is easy to learn, require basic knowledge with minimal effort on training, and basic hardware. [14]

5.3.5 Applications

1) Initial cooling system layout – In an early development stage of a vehicle, typically, a few steady state operating points such as heat load, inlet and ambient temperatures and maximum allowable temperatures are inputs which are critical conditions for the cooling package. A very quick analysis of different radiators cores, radiator sizes, cooling package arrangements, fan rpms, etc. can be easily be determined.

2) Coupled 1D-3D simulation and fine tuning – In later phases of the development of a cooling system, the typical approach is to perform isothermal CFD simulations and use the resulting mass flows to calibrate the 1D KULI model.

3) Railroad cooling system simulation, which can be diesel or electric powered.

4) Cabin cooling simulation.

5) Electric vehicle range prediction through simulation models. [14]

5.4 Cooling system modeling for optimization through KULI software

5.4.1 Simulation model inputs

As we know, optimal and efficient use of energy at any operating point of the vehicle is very important. Modeling of the cooling system will effectively optimize vehicle performance. Here, our main aim for this modeling is to finally get the fan operating data like flow rate, static pressure difference etc. that will help us to choose the best fan.

For the modeling and simulation, some important inputs must consider that are mentioned in the table 5. Some of the inputs such as fan speed, water pump speed, coolant flow rate etc. are calculated, which are described below:

1) Fan speed: It is shown in the figure 25, water pump pulley relates to crankshaft pulley through belt drive mechanism and the fan is mounted on water pump pulley. Thus, the below equation 5.1 can be used. With the known data such as diameter of both pulleys and engine speed, we can find the fan speed and thus the water pump speed. It has to note that as fan is mounted on the water pump pulley the speed of fan cannot exceed water pump speed.

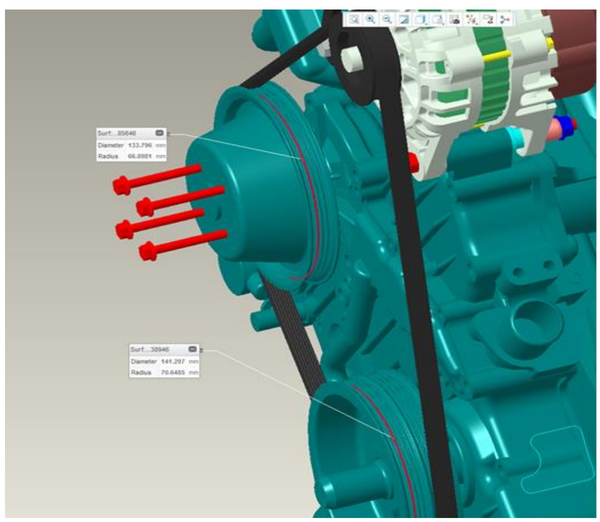


Figure 25 Crankshaft pulley and water pump pulley location

$$D_{cp} \times N_{eng} = D_{fp} \times N_f \tag{5.1}$$

Where,

D_{cp} – Diameter of Crankshaft pulley (mm)

D_{fp} – Diameter of Fan pulley (mm)

N_{eng} – Engine speed (RPM)

N_f –Fan speed (RPM)

2) Water flow rate: The below figure 26, shows the relation between water flow rate and pump speed for the engine used. As we have calculated the pump speed above, we can easily determine the water flow rate from the below mentioned figure 26.

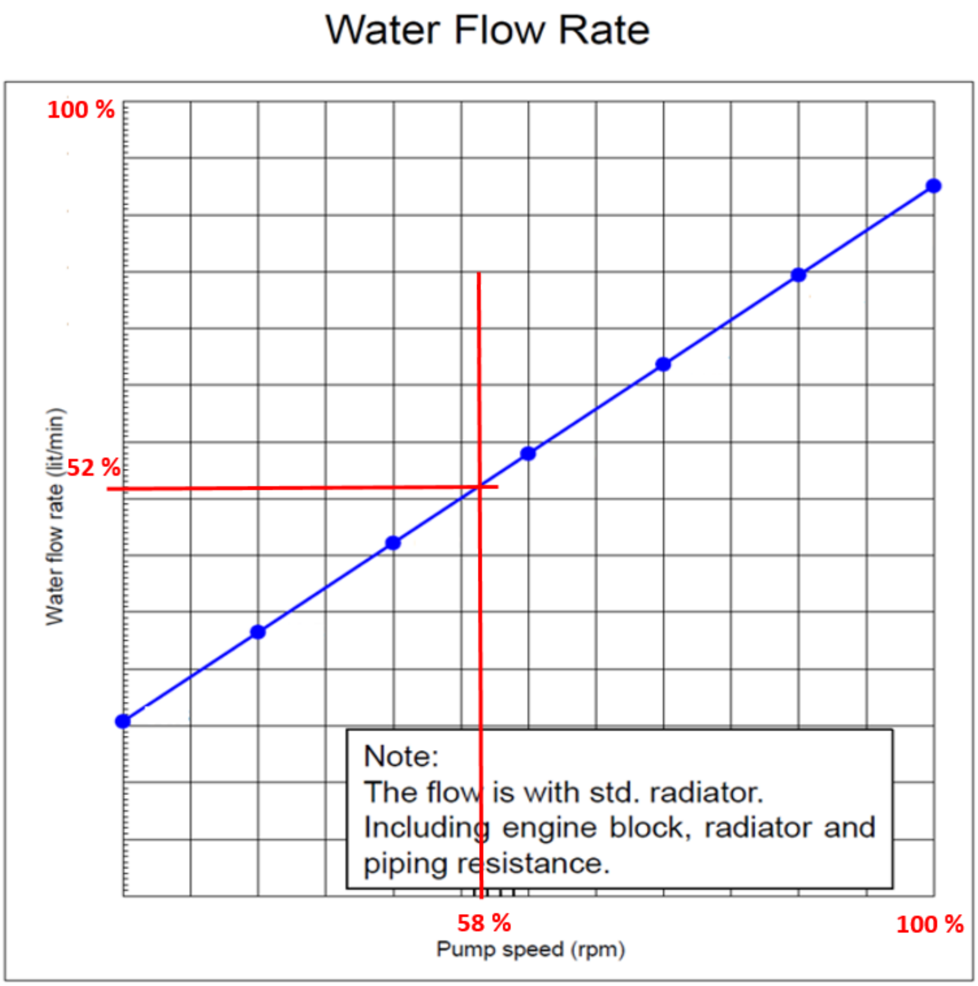


Figure 26 Relation between water flow rate and pump speed for the engine

The source of other required inputs such as cooling system data, engine cooling data, hydraulic oil data, condenser data, and air inlet data, are listed in the comment section of table 5.

		Project	
	Units	Data	Comment
Cooling system properties			
Ambient temperature	(deg C)	required	Test spec temprature
Glycol content in coolant fluid	(%)	required	Known data
Fan speed	(rpm)	required	Calculated data
Water pump speed	(rpm)	required	Calculated data
Engine cooling data			
Engine speed (rated)	(rpm)	required	From Engine manual
Engine performance	(Hp)	required	From Engine manual
Engine performance	(kW)	required	From Engine manual
Coolant flowrate	(l/min)	required	Calculated data
Max top tank temperature	(deg C)	required	Known data
Max. allowed coolant temperature	(deg C)	required	From Dyno cooling test result
Max deviation between Radiator In / Out	(deg C)	required	From Installation manual
Heat rejected to coolant	(kW)	required	From Engine manual
Max pressure drop across the system	(bar)	required	Known data
Max pressure drop of the water cooler including tank	(bar)	required	From KULI
Hydraulic oil cooling data			
Hyd oil flowrate through oil cooler	(l/min)	required	From Installation manual
Max oil cooler inlet temp	(deg C)	required	From Dyno cooling test result
Calculated heat rejection	(kW)	required	From Installation manual
HVAC condenser properties			
heat rejected to refrigerant	(kW)	required	Known data
Air inlet			
Max Air flow for Air filter calculation	(m3/min)	required	From Engine manual

Table 5 Required technical inputs for KULI modeling

5.4.2 Simulation modeling for 1D cooling system at steady state conditions

For the modeling, architecture of KULI system modules has to build such as radiator module, hydraulic oil cooler module, condenser module, fan module, built in resistance (BiR), pipe and hose subsystems. Technical inputs, from table 5, should add in the respective modules. These modules are shown in figure 29 with labels.

Built in resistance is added as a separate module because the cooling air is passes through the heat exchanger grill, guiding blades, and fans thus it gets flow resistance from blades, outlet distortions, deflections and contractions causing a pressure loss between intake and exit.

Modeling such flows needs enormous input data, calculation, and expenditure. Therefore, the flow resistances are recalculated from measurements. The pressure loss depends mainly on the flow through the system, no matter the extension of the touched area. Due to that it is allowed that only one built in resistance (engine bay) is modeled in a plane normal to the flow direction. [15].It is shown in figure 29 (inside orange dotted line).

To connect the radiator and the engine, hoses are required. Therefore, it is important to have pipe and hose subsystems which is shown in figure 29 (inside red dotted line). Pipe and hose subsystems data can be taken from the pressure loss calculation excel data for radiator water hoses. This system is shown in the figure 27 with one of its submodules.This submodules contains geometrical inputs such as section length, diameter , bend radius, and bend angle of water hoses.

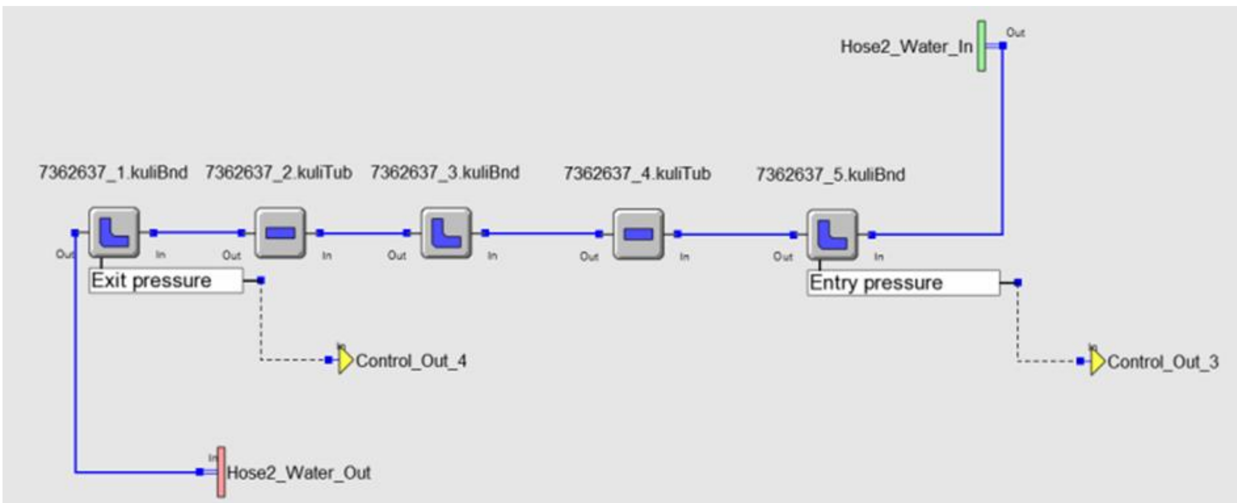


Figure 27 Radiator out hose subsystem

In figure 28, 3D simplified representation of cooling system has shown. It gives the general idea how the cooling system main components are positioned with their respective sequence. We can see in the extreme left the condenser (as an area resistance in violet colour), then the radiator cum hydraulic oil cooler (in blue cum red colour), then fan (in orange colour), and finally BiR (in pink colour).

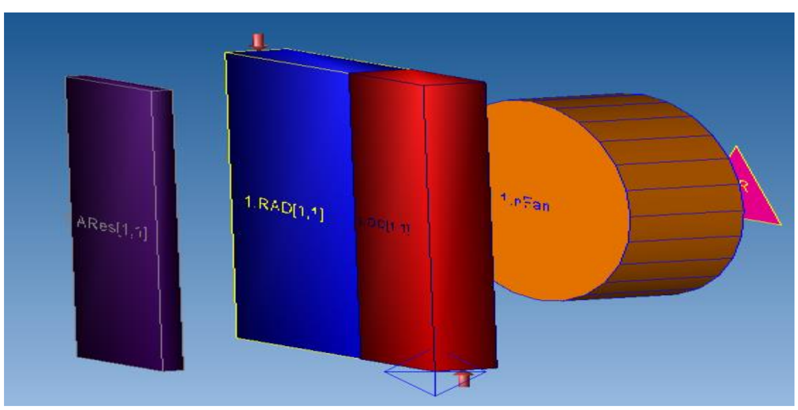


Figure 28 3D simplified representation of cooling system

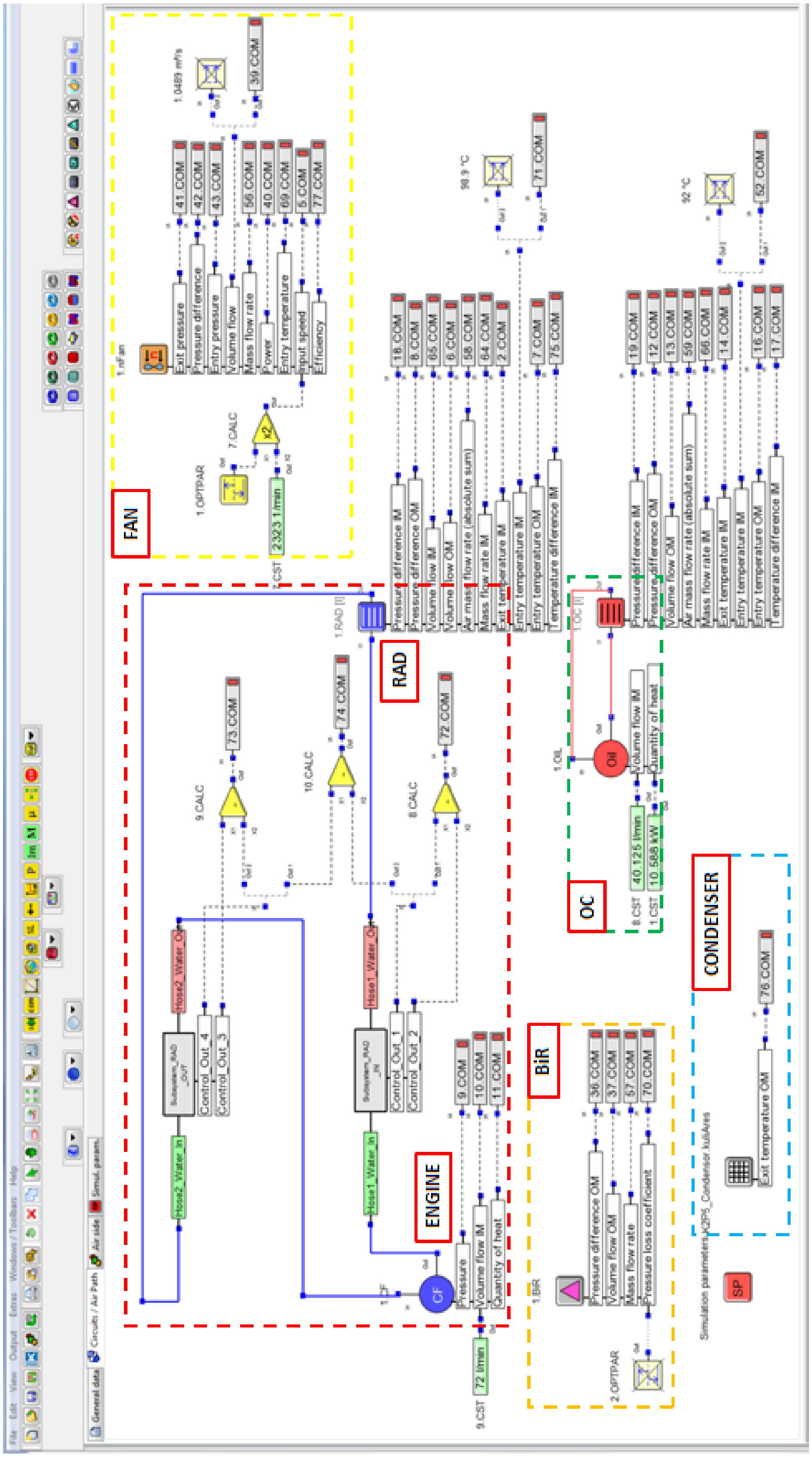


Figure 29 Simulation model of the cooling system

5.5 Simulation result, analysis, and fan selection

5.5.1 Simulation result and analysis

From the simulation model, we found two important datas, it was operating point at which fan has to run.These operating points are:

1) Airflow
2) Static pressure difference

With the help of these operating points further we will be able to select the best fan for our need.

5.5.2 Fan selection

From simulation result, we have two important fan operating point that is airflow and static pressure difference which can be seen in table 6. In this table, technical, fan geometrical, and material data are shown as inputs to choose various fans from different suppliers.

FAN A is from the chosen supplier, FAN B and FAN C are from Wingfan suppliers selected from their free online software named as “Select” and last FAN D is from Multiwing supplier selected from their free online software named as “Optimiser”. These four fans are used as an example to show the way to choose the best from them.

		FAN A	FAN B	FAN C	FAN D
INPUT	Unit	Supplier fan	Wingfan_select software		Multi wing_optimiser software
Diameter	mm	460,0	460,0	460,0	460,0
Tip clearance	mm	13,6	13,6	13,6	13,6
Volume flow_from KULI result	m³/s	1,048	1,048	1,048	1,040
Pressure difference_from KULI result	Pa	542,6	542,6	542,6	542,0
Engagement temp	°C	95,0	95,0	95,0	95,0
Blade material	NA	PAG	PAG	PAG	PAG

Table 6 Inputs to select various fans from different suppliers

Figure 30, figure 31, and figure 32 shows the fan curve for these four fans. These curves give lots of information regarding the behavior of static pressure, static efficiency and power consumption at various flowrates.

At specific flowrate (volume flow) and pressure difference as shown in table 6, it provides information about the fan speed, fan static efficiency, and fan power consumption.

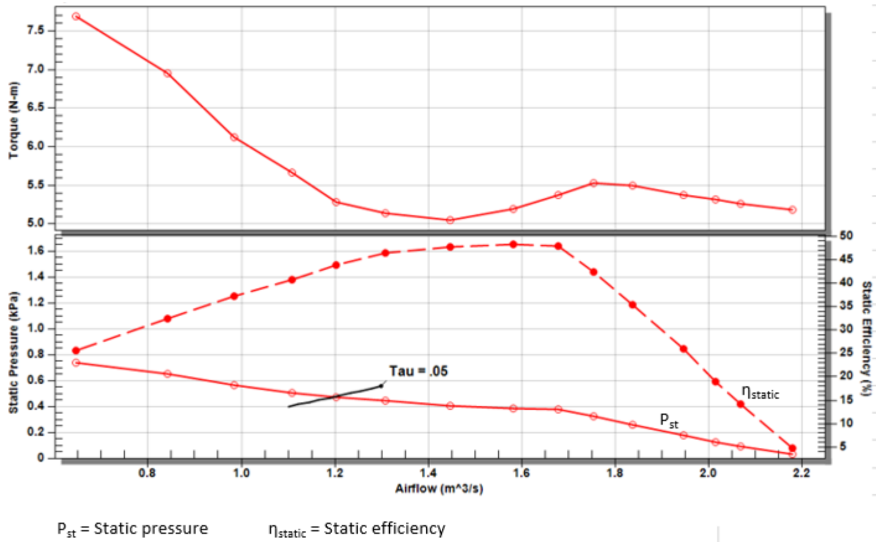


Figure 30 Fan curve for FAN A

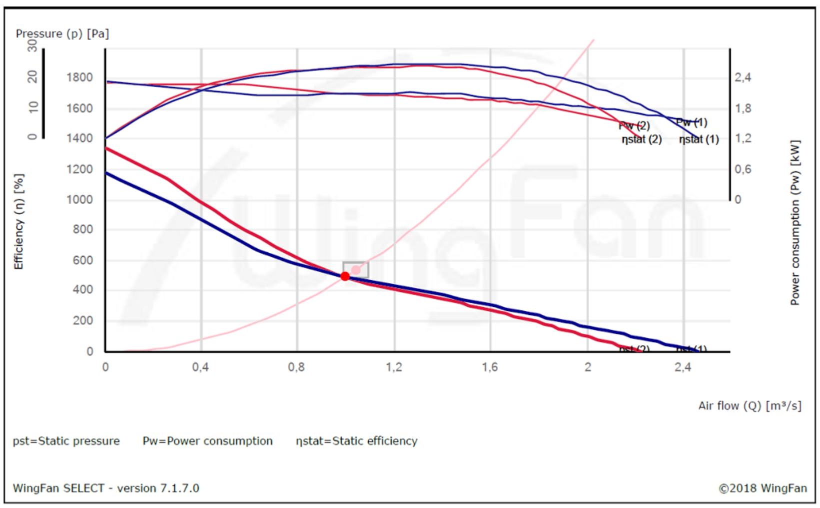


Figure 31 Fan curve for FAN B and FAN C

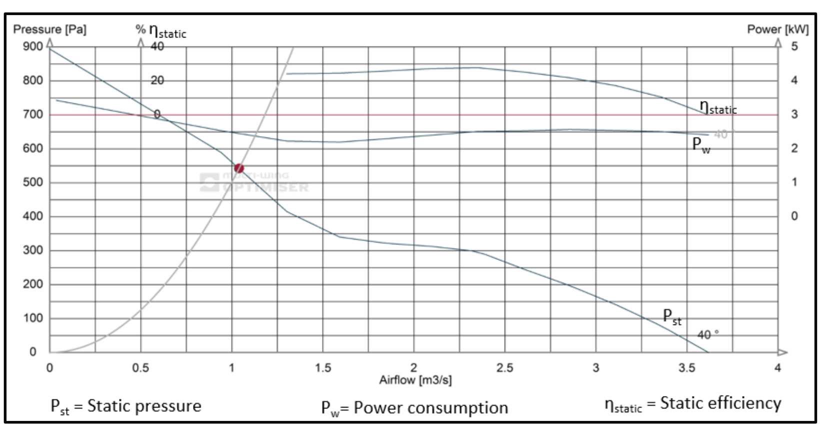


Figure 32 Fan curve for FAN D

Fan supplier data exported into KULI format and after its post processing through KULI post processor named as KULI lab, the final data is received which is shown in table 7.

		FAN A	FAN B	FAN C	FAN D
OUTPUT	**Unit**	**Supplier fan**	**Wingfan_select software**		**Multi wing_optimiser software**
Fan speed	**rpm**	2323,000	4115,258	3817,165	2320,000
Static efficiency	**%**	39,052	23,564	23,331	23,000
Power consumption	**kW**	1,456	2,414	2,439	2,450

Table 7 Comparison of the various fan output

In table 7, there are variations in the fan speed, static efficiency and power consumption from different fan suppliers though the input is same for all. Reasons could be that the fan supplier is not making the fan for our application **or** their online free software are limited to only few fans for our required conditions **or** behavior of fan curve is dependent on numerous factors therefore possibly our operating point is not the best sweet point for this curve.

To choose the best from them, we have considered some criteria:

1) Lowest fan speed
2) Lowest fan power consumption
3) Maximum fan static efficiency

From table 7, we found FAN A suits best from the rest of the fans as due to low power consumption and good fan static efficiency that will lead to reduce in fuel consumption and better torque for the vehicle. The right fan helps to maintain the good radiator performance.

6 Conclusion

1) The mechanical engine and its accessories were packaged with only few modification in the existing parts, used mostly the parts in production, and with the design of few new parts. This led to less investment as well as less time to build the new machine.
2) CAD for the Air intake system has approved, selected the suitable air filter through calculation, and designed air hoses and sent its drawings to the supplier for manufacturing.
3) Estimated the pressure losses in the air and water hoses through calculation and comparison with the KULI model with close approximation. Modelling of cooling system through KULI software takes time because of unavailability of technical data of radiator and oil cooler at initial stages. Thus, helps in early design of hoses and its manufacturing thus saves a lot of time.
4) Simulation modeling for the optimization of the cooling system through KULI software and use the simulation results to select the best fan for the required operating point that will leads to reduce fuel consumption and better torque for the vehicle.

7 Future work

1) This simulation model is based on calculation of primary inputs thus in future it has to calibrate with the practical results.

2) The sequential methodology used in this thesis can be used to get some knowledge while developing a new machine.

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