Calculation and Analysis of Temperature and Pressure Drop of Exhaust Gas in the Front Pipe of Engine Exhaust

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ABSTRACT

Temperature and pressure plays a critical role in the engine performance. The exhaust gases coming out of the engine needs to be treated before they are let into the atmosphere. The treatment of gases is done using various catalysts in the catalytic converter. For these catalysts to work properly the exhaust gas temperature plays a vital role. This paper deals with the creation of a tool which calculates the temperature and pressure drop of the exhaust gas in the front pipe of the exhaust system, (i.e. pipe starting from engine outlet till the gasses reach the ATS, i.e. After Treatment System) of an engine. The tool is created in visual studio using visual basis. For calculation of the temperature and pressure drop, the exhaust line is discretized into finite element of 1mm. Then the temperature and pressure drop in this finite element is calculated. The procedure is continued for the entire pipe and then the total temperature and pressure drop in the pipe is calculated.

Keywords. Heat transfer due to conduction, convection and radiation, conductive resistance, convective resistance to the heat flow, pressure loss due to friction and bend.

I. INTRODUCTION

Automobile engines derive power by burning gases and this process is known as combustion. The combustion takes place within the engine and as a result harmful gases are released to the atmosphere. Since the burnt gases contain very harmful materials, they are not released to the environments directly. The exhaust gasses are treated as they pass through the exhaust system, which eliminates the most harmful materials. Diesel engines are considered as one of the largest contributors to environmental pollution caused by exhaust emissions, and they are responsible for several health problems as well. Many policies have been imposed worldwide in recent years to reduce negative effects of diesel engine emissions on human health and environment. A lot of work has been carried out on both diesel exhaust pollutant emissions and after treatment emission control technologies. The exhaust gases from engine contain harmful gases like carbon monoxide (CO), oxides of nitrogen (NOx), hydrocarbons (HC), Diesel particulate Matter (DPF) etc. These gases needs to be treated and converted to less harmful gases before it is let into the atmosphere

Catalytic converter is the main component in engine exhaust system that converts the harmful gases so that it can be let into the atmosphere. A catalytic converter is a large metal box, present underside of the automobile. It has two pipes coming out of it. One of them (the converter's input) is connected to the engine and brings in hot, polluted gases from the engine's cylinders. The second pipe (the converter's output) is connected to the tailpipe (exhaust). As the gases from the engine fumes blow over the catalyst, chemical reactions take place on its surface, breaking

apart the pollutant gases and converting them into gases that are less harmful to the environment.

II. OBJECTIVE

1. To develop a tool to calculate the temperature and pressure drop in the exhaust front pipe.
2. Selection of the best pipe routing design depending on the temperature and pressure drop in the pipe.
3. To find the critical region in the pipe where there is more temperature and pressure drop.
4. Integration of the tool with NX design software, so that the designer can access the tool directly during design of pipe.

III. TREATMENT OF EXHAUST GAS

Catalytic converter is a ceramic or metallic honey comb structure that facilitates the reactions and converts toxic exhaust gases into harmless gases. The honeycomb structure allows the gases touch a larger area of catalyst at once, so they are converted more quickly and efficiently. The catalytic converter is preferred to locate closer to engine to utilize the exhaust gas temperature to the maximum possible extent. Due to the package constraint they can be placed away but in that case it should be provided with external source heat energy. This heat energy is very necessary for the reactions to happen inside the catalytic converter.

There are two different catalysts in a catalytic converter.

· One of them converts the nitrogen oxides using a chemical reaction called reduction (removing oxygen). This breaks up nitrogen oxides into nitrogen and oxygen gases.

· The other catalyst works by an opposite chemical process called oxidation (adding oxygen) and turns carbon monoxide into carbon dioxide. Another oxidation reaction turns unburned hydrocarbons in the exhaust into carbon dioxide and water.
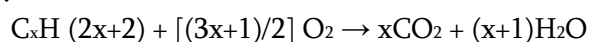
Types of catalytic converter
i. Three way catalytic converter

Used in Petrol engines and it facilitates three reactions which are as follows,

1) Oxidation Reactions. Converts carbon monoxide into carbon dioxide
$$2CO + O_2 \rightarrow 2CO_2$$
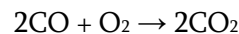
2) Converts Un-burnt or partially burnt hydrocarbons into carbon dioxide and water
$$C_xH_{(2x+2)} + [(3x+1)/2] O_2 \rightarrow xCO_2 + (x+1)H_2O$$

3) Reduction Reaction. Converts Oxides of nitrogen into Nitrogen and oxygen
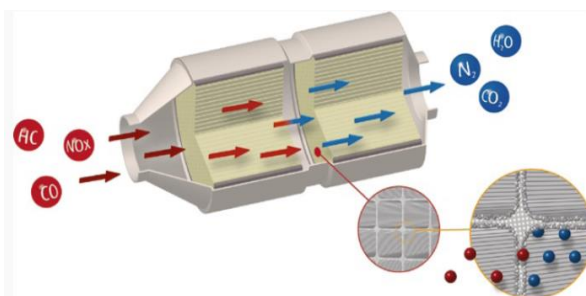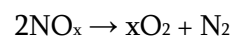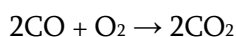$$2NO_x \rightarrow xO_2 + N_2$$

Figure 1. Three way catalytic converter

ii. Diesel Oxidation Catalyst

The diesel oxidation catalyst is designed to oxidize carbon monoxide, gas phase hydrocarbons.

1) Oxidation Reactions. Converts carbon monoxide into carbon dioxide
$$2CO + O_2 \rightarrow 2CO_2$$

2) Converts unburnt or partially burnt hydrocarbons into carbon dioxide and water
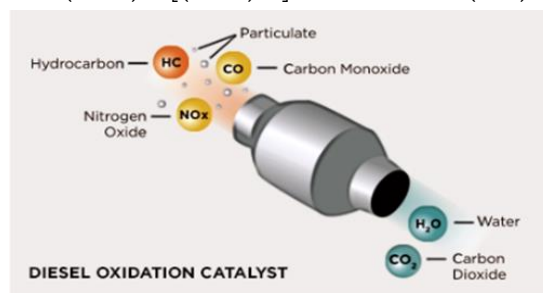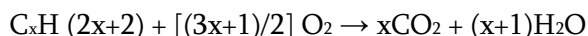$$C_xH_{(2x+2)} + [(3x+1)/2] O_2 \rightarrow xCO_2 + (x+1)H_2O$$

Figure 2. Diesel Oxidation Catalyst

IV. PROBLEM STATEMENT

· For the Catalytic converter to work efficiently the exhaust gasses should be maintained at higher

temperature. But as the exhaust gases flow from engine outlet to the catalytic converters inlet a great amount of heat is lost to the atmosphere.

- The designer designs the pipe and sends it to the CFD (Computational Fluid Dynamics) for the analysis, to check the temperature and pressure drop that may incur in the pipe. It takes around 3 to 4 days to get the result.

V. MODES OF HEAT TRANSFER

Temperature drop in the exhaust gas mainly occurs due to heat transfer by conduction, convection and radiation.

1. Conduction

Thermal conduction is the transfer of heat (internal energy) by microscopic collisions of particles and movement of electrons within a body. The microscopically colliding objects, that include molecules, atoms, and electrons, transfer disorganized microscopic kinetic and potential energy, jointly known as internal energy. Conduction is the most significant means of heat transfer within a solid or between solid objects in thermal contact. Conduction is greater in solids because the network of relatively close fixed spatial relationships between atoms helps to transfer energy between them by vibration.

The law of heat conduction, also known as Fourier's law, states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows.
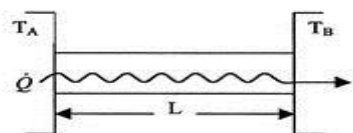
Fig 3. Heat Transfer due to conduction

$$Q = - k * A * \left(\frac{T_A - T_B}{L}\right)$$

'A' is the area, at right angles to that gradient, through which the heat flows
T_A and T_B are the temperatures at the 2 ends of the material of length L.

(-) sign indicates the gradient of temperature $\left(\frac{T_A - T_B}{L}\right)$ is negative i.e. decreases with distance.
'k' (W/m K) is known as Thermal conductivity.
The equation can be re-arranged as

$$Q_{Cond} = \frac{T_1 - T_2}{R_{wall}} \text{ (W)}$$

Where, $R_{wall} = \frac{L}{k * A}$ (°C / W)
Similarly Thermal resistance for a pipe or cylindrical element is given by,

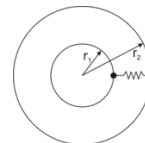$$R_{cylinder} = \left(\frac{Ln\left(R_2/R_1\right)}{2 * \pi * L * k}\right)$$

Figure 4. Thermal resistance in a cylindrical pipe

Where, R_2 is the outer radius of the pipe,
R_1 is the inner radius of the pipe,
R_{wall} is the thermal resistance to conduction

2. Convection

Convective heat transfer, often referred to simply as convection, is the transfer of heat from one place to another by the movement of fluids. Convection is usually the dominant form of heat transfer in liquids and gases. Although often discussed as a distinct method of heat transfer, convective heat transfer involves the combined processes of unknown conduction (heat diffusion) and advection (heat transfer by bulk fluid flow).

The rate of convection heat transfer is expressed by Newton's law of cooling. Newton's law states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings while under the effects of a breeze. The constant of proportionality is the heat transfer coefficient. The law applies when the coefficient is independent, or relatively independent, of the temperature difference between object and environment.

$$Q_{Conv} = h A (T_s - T_a)$$

Where, T_s is the surface temperature of the body (K),
T_a is the ambient temperature of the surrounding (K),

h is the heat transfer coefficient W/ (m2K)

The convective heat transfer coefficient 'h', depend on type of media, gas or liquid, the flow properties such as velocity, viscosity and other flow and temperature dependent properties.

Convective heat transfer coefficient is found using Nusselt number. In heat transfer at a boundary within a fluid, the Nusselt number (Nu) is the ratio of convective to conductive heat transfer across (normal to) the boundary.

$$Nu = \frac{\text{Convective heat transfer}}{\text{Conductive heat transfer}} = \frac{h}{\left(\frac{k}{L}\right)}$$

$$h = \frac{Nu * k}{L}$$

Where, k is the thermal conductivity of the gas,

L is the characteristic length. If the flow of gas is through the cylindrical pipe, then L is the inner diameter of the pipe.

Here the Nusselt number is calculated using Gnielinski correlation, which given by,

$$Nu = \frac{f}{8} * (Re - 1000) * \frac{Pr}{\left[1 + 12.7 * \left(\frac{f}{8}\right)^{0.5} * \left(Pr^{2/3} - 1\right)\right]}$$

Where, f is the Darcy friction factor that can be obtained from the Moody chart

Re is the Reynolds number of the gas

Pr is the Prandlt number of the gas

Convective resistance is the resistance offered to the heat flow due to convection. From Newton's law of cooling, for steady convection on a constant area A, can be written as

$$Q_{Conv} = h * A * (T_s - T_a)$$

This can be re-arranged as

$$Q_{Conv} = \frac{T_s - T_a}{R_{Conv}} \text{ (W)}$$

Where, $R_{Conv} = \frac{1}{h * A}$ (°C / W)

R_{Conv} is the resistance against heat Convection.

3. Radiation

Thermal radiation is energy transfer by the emission of electromagnetic waves which carry energy away from the emitting object. All matter with a temperature greater than absolute zero emits thermal radiation. When the temperature of a body is greater than absolute zero, inter-atomic collisions cause the kinetic energy of the atoms or molecules to change. This results in charge-acceleration and dipole oscillation which produces electromagnetic radiation, and the wide spectrum of radiation reflects the wide spectrum of energies and accelerations that occur even at a single temperature. The relationship governing the net radiation from hot objects is called the Stefan-Boltzmann law.

The Stefan–Boltzmann law describes the power radiated from a black body in terms of its temperature. Stefan-Boltzmann law states that, "The thermal energy radiated by a blackbody radiator per second per unit area is proportional to the fourth power of the absolute temperature". The total intensity radiated over all wavelengths increases as the temperature increases. The amount of thermal radiation emitted increases rapidly and the principal frequency of the radiation becomes higher with increasing temperatures.

$$Q_{Rad} = \varepsilon * A * \sigma * T^4$$

Where, ε is the emissivity of the grey body,

A is the total surface area,

T is the temperature of the body (K)

σ is the Stefan-Boltzmann constant = $5.6703 * 10^{-8}$ (W m^{-2} K^{-4})

If the hot object is radiating energy to its cooler surroundings at temperature Tc, the net radiation loss rate takes the form

$$Q_{Rad} = \varepsilon * A * \sigma * (T_s^4 - T_a^4)$$

Where, T_s is the surface temperature of hot body (K)

T_a is the ambient temperature (K)

VI. PRESSURE DROP IN A PIPE

Pressure loss in a pipe mainly occurs due to two factors. They are pressure loss due to friction and pressure loss due to bend in pipe.

1. Pressure loss due to friction

$$P_{loss} = \frac{f_{in} * \rho_{in} * L * V_{in}^2}{2 * D_{in}}$$

Where, f_{in} is the friction factor at the inner surface of the pipe

ρ_{in} is the density of the exhaust gas in the pipe (kg / m³)

L is the length of the pipe (m)

V_{in} is Velocity of exhaust gas (m³/s)

D_{in} is the inner diameter of the pipe (m)

2. Pressure loss due to bend

$$P_{bend} = \frac{k_b * \rho_{in} * V_{in}^2}{2}$$

Where, k_b is the bend loss coefficient

ρ_{in} is the density of the exhaust gas in the pipe (kg / m³)
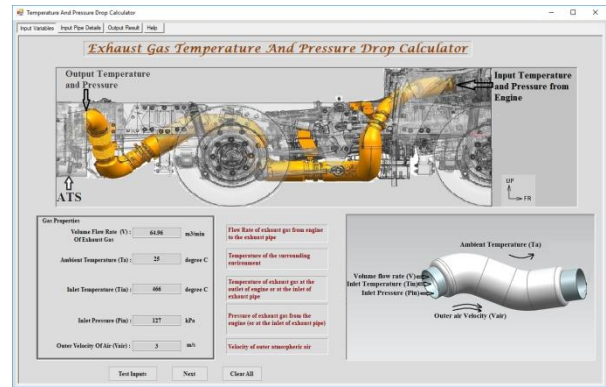
V_{in} is Velocity of exhaust gas (m² / s)

VII. TEMPERATURE AND PRESSURE DROP CALCULATOR

- First the pipe is created in NX modelling software using tube option.
- Next to calculate the temperature and pressure drop in the pipe, TPC icon (TPC stands for Temperature and Pressure drop Calculator) created in NX is clicked.
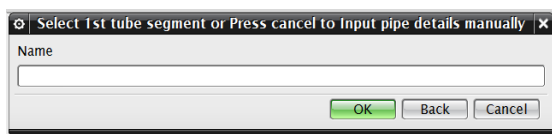

Figure 5. Dialog prompt for pipe selection

- If the pipe dimension details needs to be taken from NX, then all the pipe segments are selected and the press OK.
- Next the tool window will appear. When the tool pops up, the first page appears as shown in Fig 6.
- Next fill all the input details like Volume flow rate of the exhaust gas, ambient temperature of the outer atmosphere, inlet temperature of the exhaust gas, inlet pressure of the exhaust gas, outer air velocity and roughness of inner surface of the pipe.
- Once all the values in the first page are filled next button is pressed. This will automatically display the next page, where pipe details needs to be filled.

Figure 6. Tool first page

- In the 'Input Pipe Details' tab all the pipe details needs to be filled.
- Once the number of pipe set details is filled, then the values of Pipe outer diameter, Pipe Thickness, Pipe material, Insulator outer diameter, Pipe cover thickness, Insulation material are filled.
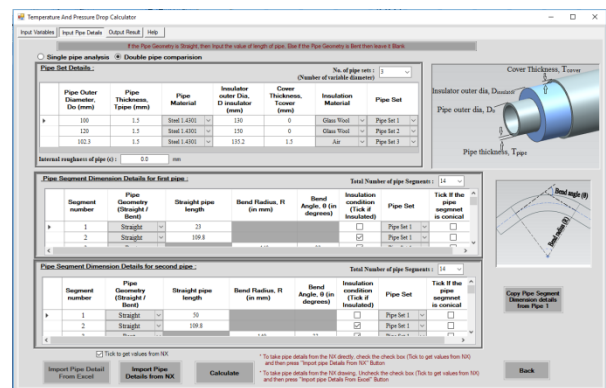

Figure 7. Tool second page

- Also the image on the right hand side of the screen will help to give a clear idea of the data that needs to be filled.
- Next the pipe segment dimensions should be filled.
- Here the details like pipe segment shape, segment length, insulation condition, and pipe set details are filled.
- The pipe segment dimension details can also be directly taken from NX model by clicking on the button 'Import pipe details from NX'.
- The inputs like pipe shape, pipe length, bend radius and bend angle of pipe can be imported directly from NX.

- After importing the values from NX Insulation condition and pipe set details needs to checked.
- Next press calculate button to get the output result.
- In the output page we will get both the pressure drop and the temperature drop graphs as shown in fig 9.
- Also we will get the details like the total length of the pipe, percentage of insulation in the pipe, total temperature and pressure drop in the entire length of the pipe, segment in which there is maximum temperature drop.
- By looking at the results the designer will come to know at which region of the pipe there is maximum temperature and pressure drop, and hence he will be able to do the modification required to reduce the temperature and pressure drops.
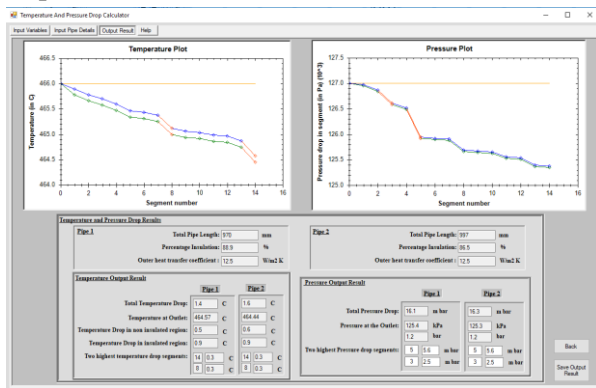

Figure 8. Tool output page

- Also if the designer has to select a pipe from two sets of pipe designs variants, then he can easily do it by checking the temperature and pressure drops in the pipe for those variants, and select the one which has least temperature and pressure drop.

VIII. METHODOLOGY

1. First all the parameters like exhaust volume flow rate, gas temperature, exhaust gas pressure, ambient temperature are given as input.
2. Next the pipe details like length of pipe, diameter of pipe, thickness of pipe, thickness of insulation, roughness of pipe are given as input and calculate button is pressed.
3. Once the calculate button is pressed the tool selects the first segment of pipe and discretize the pipe into a length of 1mm.
4. Next for the discretized 1mm segment the tool checks weather the segment is insulated or non-insulated.
5. Next the properties like specific heat, thermal conductivity, Prandlt number of ambient air and gas are calculated based on it temperature and pressure.
6. Next flow velocity, Reynolds number, friction factor, Nusselt number is calculated for both exhaust gas & outer atmospheric air.
7. Using the above values heat transfer coefficient for exhaust gas &outer atmospheric air is calculated.
8. Next for the discretized 1mm length the total resistance offered by the pipe to heat flow is calculated considering the insulation condition.
9. Next from the resistance value obtained the heat lost by the exhaust gas to the atmosphere is calculated.
10. From the value of heat lost and the segment pipe resistance, the surface temperature of the pipe is calculated.
11. From the value of surface temperature the amount of heat lost due to radiation is calculated.
12. Using the values of heat lost due to radiation and convection, the drop in temperature of the gas at the end of 1mm segment is calculated.
13. This value is stored to find the total temperature drop in the entire pipe.
14. The value is also plotted in the temperature v/s pipe length graph.
15. Next the tool identifies weather the segment is a straight or a bend segment.
16. First the friction factor of the pipe is calculated using Moody's friction factor.
17. If the pipe segment geometry is straight, the tool calculates the pressure loss due to friction i.e. the frictional pressure loss.
18. If the pipe segment geometry is bent, then the pressure loss is calculated as a sum of pressure

loss due to friction and the pressure loss due to bend.

19. The obtained pressure loss is stored to calculate the total pressure loss in the pipe.

20. Simultaneously the pressure drop is plotted in a graph of pressure drop v/s pipe length.

21. This completes the first loop. Next the same procedure is carried out for the next 1mm discretized length.

22. When the temperature and pressure drop for all the discretized elements are calculated, next pipe segment is considered.

23. If the calculation of temperature and pressure for the entire pipe segment is calculated, then the tool comes out of the loop and sum up the total temperature and pressure drop in the entire length of the pipe.
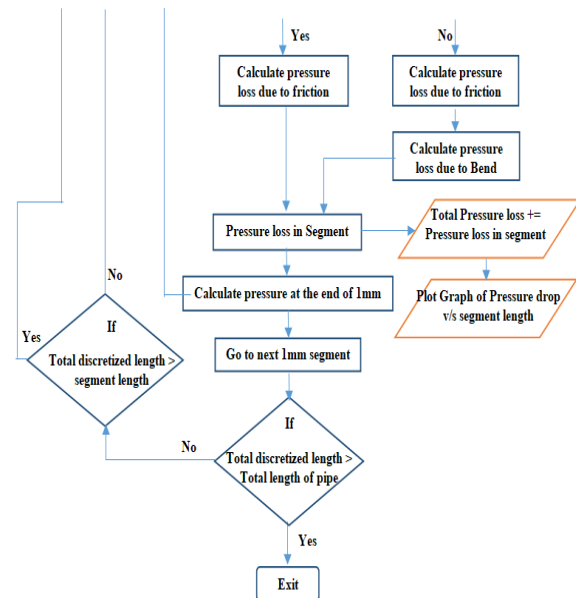

Figure 9. Temperature and Pressure drop Calculation flow chart

IX. VALIDATION OF THE TOOL RESULTS

The temperature and the pressure drop vary based on the input parameters, pipe and insulation materials, and ambient temperature and pressure. The temperature and pressure drops are calculated for various pipes having varying lengths, input parameters and varying materials. The results of temperature and pressure drops are then matched with that of a commonly used 1D tool named GT-Suite (Gamma Technology)

The results obtained from the tool are matched with that of the GT-Suite. There is a maximum deviation of 1°C in the temperature and 1.5 (m Bar) in pressure drop. The results are matched for various sets of exhaust pipes with GT-Suite and the results are matching with an approximation of 12% for both temperature and pressure drops.

The tool results are also tested with that of GT-Suite for simple straight pipes with and without insulation, and a bent pipe. The results obtained from the tool are matching with the results of GT-Suite up to two decimal places for the temperature drop and up to one decimal places for the pressure drop. The results are as shown in Figure 10 and Figure 11.
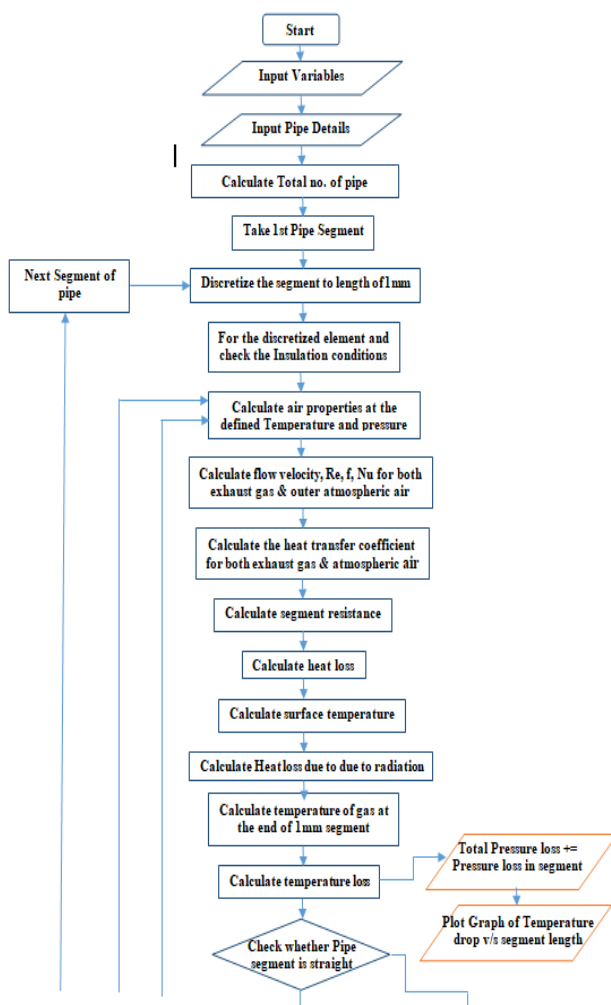
	Developed Tool Result	GT Suite Result	CFD Result	Result deviation with GT Suite	Result deviation with CFD
Temperature Drop °C	1.5	1.4	1.44	0.1	0.06
Drop (m..)	16.3	17.4	16.74	1.1	0.44

Figure 10. Result comparison with GT-Suite and CFD

	Pipe no.	Developed Tool Result	GT Suite result	Deviation
Temperature Drop °C	Pipe no. 1	12.16	11.4	0.76
	Pipe no. 2	11.6	10.6	1
	Pipe no. 3	4.98	5.1	-0.22
	Pipe no. 4	5.9	6.7	-0.8
	Pipe no. 5	3.5	3.8	-0.3
Pressure Drop (m bar)	Pipe no. 2	5.4	4.8	0.6
	Pipe no. 3	12.9	11.5	1.4
	Pipe no. 4	19.1	20.5	-1.4
	Pipe no. 5	18.4	19	-0.6

Figure 11. Result comparison for exhaust pipes

X. FUTURE SCOPE

1) The tool developed is a 1-D tool i.e. it calculates and provides the temperature and pressure drop of the exhaust gas in a steady state. Further development can be done to develop a 3-D tool to calculate the results in a transient state.

2) The tool can be made to select all the pipe dimensions like pipe diameter, pipe thickness Insulator diameter and cover thickness automatically from NX.

3) Checking the pipe insulation condition i.e. whether the pipe segment is insulated or non-insulated can be automated.

XI. CONCLUSION

1) Temperature and pressure drop in a pipe can be calculated in a single tool.

2) The temperature and pressure drop at any point along the pipe length can be calculated.

3) The pipe segments with maximum temperature and pressure drop can be found out.

4) Tool is integrated with UG-NX software so that the designer can directly access the tool from design software.

5) Tool can take the pipe dimensions directly from design model.

6) Tool results are compared with the GT-Suite results for validation and the results match with an average deviation of 1℃ for temperature drop and 2mBar for pressure drop.

XII. ACKNOWLEDGEMENT

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