

# NUMERICAL MODELLING OF HEAT TRANSFER IN ENGINE EXHAUST MANIFOLDS

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**Abstract:** *The purpose of the paper is to study the heat transfer in the exhaust manifold of a naturally aspirated diesel engine. The work has started from the exhaust manifold of the test engine D30 which was redesigned in CATIA V5, then pre-processed in Comsol Multiphysics. The results of the post-processing phase have generated temperature, velocity, pressure and Reynolds number fields which were compared with experimental data from engine dynamometric test. For a higher accuracy the temperatures of exhaust manifold surfaces were measured both with IR Camera Imager and thermocouples.*

**Key words:** *combustion engines, exhaust flow, heat transfer.*

## 1. Introduction

The heat transfer in internal combustion engines is an important issue over decades; it affects power, efficiency, and emissions [2], as well as the potential of waste heat recovery. Within all the phases of engine cycle and in all engine components there is a continuous variation of the temperature fields, being met all forms of heat transfer: conduction, convection, and radiation. Most of research work was concentrated to heat transfer from combustion chamber to cylinder wall towards cooling fluid being issued semi-empirical global heat transfer correlations [3].

For compression ignition engines the energy balance indicates that the cooling loss is 16-35% and exhaust loss 23-37% from fuel energy [1]; the shares are rather similar, but the potential of energy recovery is different, being higher for exhaust gas as a result of higher temperatures. As most of the waste heat recovery (WHR) methods are aimed on the exhaust system, it is natural to study thoroughly the heat transfer from exhaust gas towards pipes and further to WHR devices, such as Thermo-Electric Generators (TEG) or Organic Rankine Cycle (ORC).

So, the purpose of the present work is to evaluate the heat transfer through an engine exhaust manifold by means of a numerical simulation which can be validated with experimental data.

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The experimental part relies on two previous works performed on the dynamometric brake on the same engine, according with the engine testing standards. The first one reports on engine heat balance terms, mainly on convective -radiative heat flow rate of engine hot surfaces [5]. The second one reports on the experimental investigation of a commercial TE device, known also as Peltier cooler, for energy harvesting [6], which was mounted on the engine exhaust manifold, which is as under study in present article. The set of data are used to initiate the numerical model of heat transfer, also indicating the values domain.

## 2. Engine Data

The thermal study of exhaust manifold heat transfer should be validated with experimental data on temperature fields during engine operation. A naturally-aspirated diesel engine, D-30 type, was selected, with main data illustrated in Table 1. It originates from the D110 tractor engine – manufactured at the Brasov Tractor Factory. The tests were performed in the Thermodynamics and Heat Engines Laboratory, on a dynamometric brake - Figure 1.



Fig. 1. *D-30 engine on the test bench*

*D-30 engine technical data*

Table 1

Engine type	Direct injection into the unitary chamber with tangential manifold
Cylinder configuration	2-cylinder, vertical, in-line
Bore x Stroke [mm]	108 x130
Displacement [L]	2.38
Compression ratio	17:1
Rated power [kW]	24
Rated speed [rpm]	1800

### 2.1. Temperature field

For two engine operation modes defined in Table 2, by speed and load, there are included data on exhaust gas temperatures and two external manifold temperatures.

In the exhaust manifold the hot exhaust gas releases heat towards the manifold walls which are further cooled by ambient air, so there is a significant difference between these temperatures. The exhaust gas temperatures were measured by thermocouple and the external manifold temperatures were measured using both thermocouple and Fluke infrared "Thermal Imager" [10].

Temperatures in the engine operation modes

Table 2

No. test	$n$ [rpm]	$F$ [brake divisions]	Exhaust gas temp. [°C]	Manifold temperature [°C]		Relative Error [%]
				Thermocouple	IR	
1.	991	10	140	74	78.7	1.3
2.	1440	13	200	140	137.6	0.6

As it can be observed, the engine operation modes are performed at lower speed and load than manufacturer declaration (Table 1) so it is reasonable to accept that the temperature field exceeds the upper limit, 200°C, which is why the temperature interval suggested for numerical simulation was recommended to be 130-300°C.

## 2.2. Exhaust gas flow rate field

Engine air, fuel and exhaust gas flow rates are calculated for the time interval,  $t_c$ , in which the engine consumes the given mass of diesel fuel of 0.100 kg. Table 3 illustrates also the hourly fuel consumption,  $C_h$ , the hourly air flow rate measured with a calibrated diaphragm,  $G_{air}$ , exhaust gas mass specific heat at constant pressure,  $c_{pexh}$ , exhaust gas constant  $R_{exh}$ , the hourly exhaust gas mass flow rate,  $G_{exh}$ , exhaust pressure loss  $\Delta p_{ev}$  and density  $\rho_{exh}$  calculated according to [9]. As a result the field of exhaust gas flow rate values is 0.03-0.045 kg/s.

Engine calculated parameters

Table 3

No. test	$t_c$ [s]	$C_h$ [kg/h]	$G_{air}$ [kg/h]	$c_{pexh}$ [J/kgK]	$R_{exh}$ [J/kgK]	$G_{exh}$ [kg/h]	$\Delta p_{ev}$ [Pa]	$\rho_{exh}$ [kg/m <sup>3</sup> ]
1.	165.3	2.178	106.92	1050.759	287.463	109.098	15000	0.891
2.	88.5	4.068	132.12	1084.944	287.348	136.188	15500	0.729

## 2.3. Exhaust gas velocity field

Exhaust gas velocity depends on its density and flowing sections. The acceptable range of density based on Table 3 values is 0.7-0.9 kg/m<sup>3</sup> and the geometry of the manifold had generated the flowing sections.

## 3. Modelling of the Exhaust Manifold

In order to obtain the computer geometrical representation of the exhaust manifold, a specialized 3D modelling software, CATIA V5, has been used [8].

Based on measurements made on the test stand combined with photographed images taken from different views, the necessary data was obtained in order to create the three-dimensional model. Having this input data, two CATIA modules have been used, mainly *part design* and *geometrical shape design*.

The approach to the modelling of the exhaust manifold was to create a shell representing the exterior surface of the engine component and then offsetting this surface to obtain the thickness of the model – Figure 2. This was done by creating multiple sketches representing sections through the shell surface at different points corresponding to the measurements on the test bench. The multi-section surface command was then used to join the sketches through patches, by sweeping two or more section curves along a defined spine. Tangent continuity has been selected for this model. The symmetry command worked efficiently for this model and was used to increase productivity. After modelling the inner and outer shells, all gaps were filled, and surfaces joined to create the solid model of the exhaust manifold. Part model could now be saved in universal .STP format for further processing.

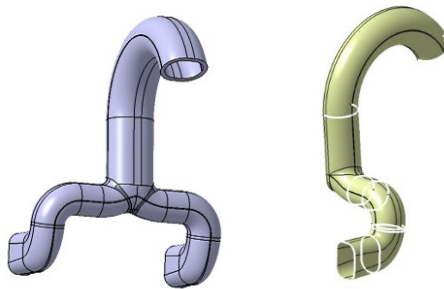


Fig. 2. CATIA multi-section surface

At the modelling stage, different small radii and small surface patches were created which can generate problems when importing into a CAE pre-processor. Major geometry problems can be corrected using Elysium CADDuctor 6.1 software [4]. This software can automatically correct surfaces that do not combine perfectly, small edges, optimizes connections, etc. Errors can occur when transferring CAD data from one engineering platform to another such as failure to import all data, failure of mesh generation; the user can adjust the surface healing criteria to meet the standards for the required application.

#### 4. Configuring the Model in COMSOL Multiphysics

After repairing the geometry, the model was imported into the COMSOL Multiphysics pre-processor [7]. Further geometry corrections can be made to optimize mesh generation by ignoring unnecessary edges or vertices. At this stage, the fluid geometric boundary must be defined by filling the model input and output cavities. This operation will be recognized by the software as splitting the geometry into two domains, one for the body of the manifold and another one for the fluid which flows through it, basically creating a control volume.

The next step is the specification of material properties - there were used the properties

of air as a replacement for the exhaust gases; for the exhaust manifold it was considered Aluminum 6063.

Defining of the boundary conditions consists of selecting the physics interfaces which are used to compute temperature fields but also velocity and pressure fields. Thermal multiphysics couplings are used to model heat transfer by conduction, convection or radiation. Fluid flow interfaces are used to simulate flow and pressure fields of liquids and gases. For the exhaust manifold, the chosen interfaces were represented by the heat transfer in solids and fluids, turbulent Low-Re  $k-\epsilon$  or Spalart-Allmaras and the multiphysics coupling between the heat transfer and fluid flow boundaries. The corresponding domains representing each geometrical entity of the control volume is necessary to be attributed at this stage, including fluid inlet (and also temperature) and the outlet. The heat transfer with external air is modeled considering convection heat transfer. The average convection heat transfer coefficient used is of  $25 \text{ W/m}^2\text{K}$ .

The inlet conditions used for model (pressure, mass flow, temperature) are the values presented in Tables 2 and 3, for Test case no.1.

The meshing of the model is an important step at this point as it enables the discretization of the geometry into small units of simple shapes. The 3D mesh generator uses tetrahedral, hexahedral, prism or pyramid mesh elements for the body of the geometry, while the boundaries in the geometry are discretized in triangles or four-sided polygons whereas edges are discretized into edge elements.

For this application, a tetrahedral mesh has been considered with the size calibrated for fluid dynamics. The number of tetrahedral elements resulted is 265410 (Figure 3.a), with minimum quality of 0.01642 and average quality of 0.6957 as is represented in Figure 3.b. Also, the Yplus dimensionless number is represented in Figure 3.c.

The convergence of segregated solver used by Comsol for velocity, pressure, temperature, and turbulence variables is presented in Figure 4.

## 5. Results Post-processing

In Figures 5-8 there are illustrated the post-processed surface temperatures, the exhaust gas velocity, the contour pressure and the Reynolds numbers, respectively.

It can be highlighted that the temperature decrease is significant at each bend, mainly due to the local pressure increase which generates a more turbulent flow that benefits convective heat transfer.

Also, the increase in section area at the junction of the two exhaust pipes highly affects the cooling of the exhaust gases where the pressure decreases significantly.

## 6. Validation by IR Thermal Imaging

In order to be trustfully used in simulation and design, the model was validated using infrared thermography performed on the engine operating in the different configurations and modes on the test bench (Figure 1). It was used a FLUKE Ti20 special IR camera [10], with a sensitivity of 0.2 K. The associated FLUKE InsideIR software package enables storing and analysing the thermal images. For the 1<sup>st</sup> operation mode (Figure 9.a) the dominant colours of the exhaust manifold only is light blue-green which indicates a mean surface

around 70-80°C.

Similarly, for the 2<sup>nd</sup> operation mode (Figure 9.b), there the same predominance of the manifold areas in the same spectrum of light blue green corresponding this time to a mean surface temperature value of 130-150°C.

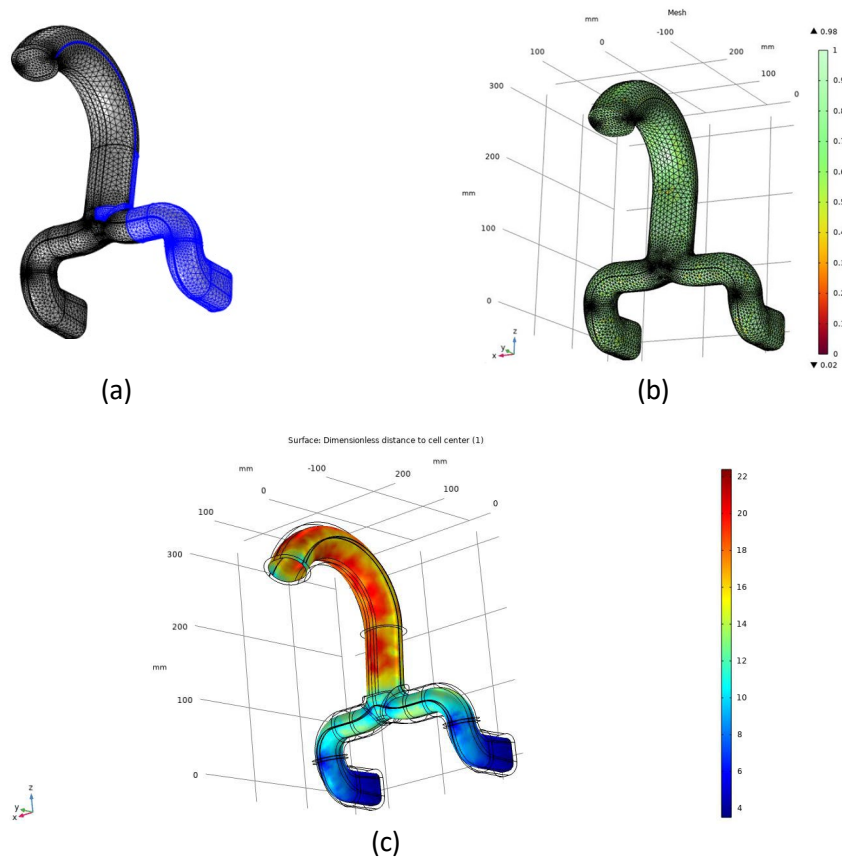


Fig. 3. *The 3D tetrahedral mesh*

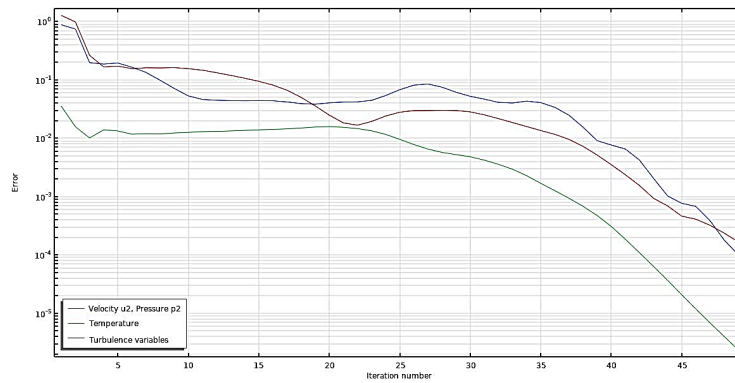


Fig. 4. *The segregated solver*

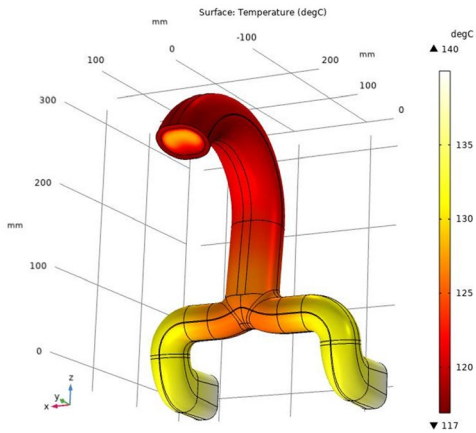


Fig. 5. Surface temperatures (K)

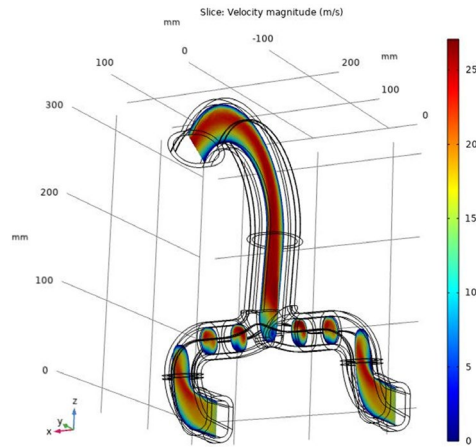


Fig. 6. Exhaust gas velocities (m/s)

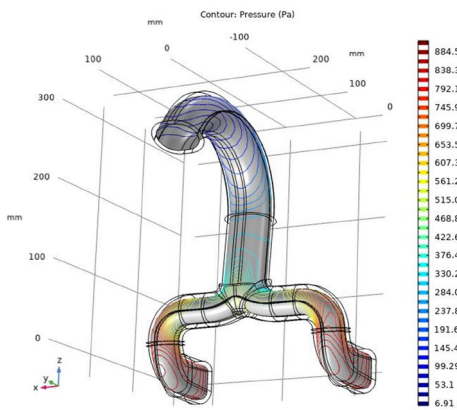


Fig. 7. Contour pressures (Pa)

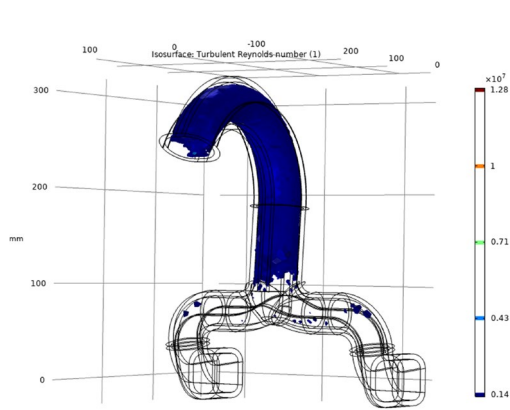
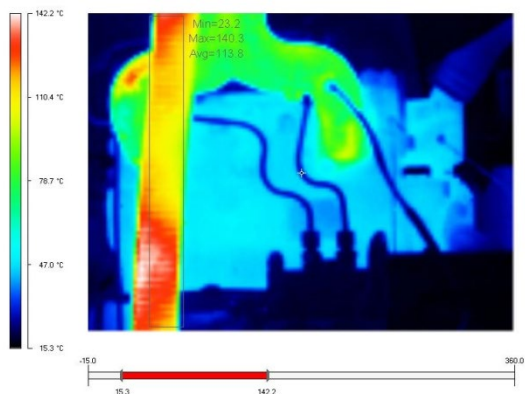
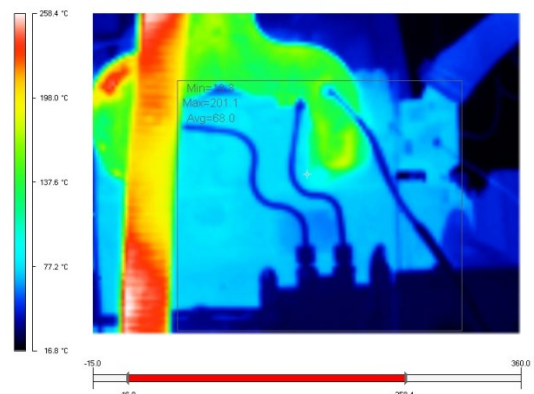


Fig. 8. The Reynolds numbers



(a)



(b)

Fig. 9. Thermal images of the operation modes

## 7. Conclusions

By using two temperature measurement techniques (IR thermography and thermocouple) the confidence on temperature reading has increased and the prediction of the temperature field within the numerical simulation has been improved. By analysing the temperature field results, one can estimate a feasible position for a waste heat recovery device or optimize the design of the manifold in order to maximize the heat transfer efficiency for this kind of application. Further work in terms of Reynolds number distribution should be refined for design optimization. Nevertheless, an isolated radiation result should be taken into account to visualize the influence of emissivity coefficient values of different manifold materials.

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