HEAT TRANSFER MODEL FOR MARINE TWO STROKE ENGINE CYLINDER

Jerzy Kowalski
Wieslaw Tarelko

Gdynia Maritime University
ul. Morska 81-87, 81-225 Gdynia, Poland
tel.: +48 58 6901331
e-mail: jerzy95@am.gdynia.pl; tar@am.gdynia.pl

Abstract

This paper deals with modeling of heat flow through cylinder structural components of a marine two-stroke engine. Especially, we paid attention on simulating of temperature distribution for the wet cylinder liner. Multidimensional equations for the transient heat conduction with the Dirichlet and Fourier boundary conditions have been applied. In particular, we applied local values for the convective and radiative heat transfer coefficients using the Fourier boundary conditions determined in a space of cylinder volume and a cooling space of the cylinder. In order to determine the temperature distribution for considered spaces, we applied the radiosity method. Simulation results have been presented in the form of a temperature field for cylinder structural components depended on the crankshaft position angle. Application of the iterative calculation method for solving differential equations of energy balance allowed us for using software easy to get. We carried out all iterative computations using MS Excel spreadsheet. This way, we could decrease the simulation cost significantly.

Keywords: *marine engine, radiosity method, heat transfer, cylinder liner, thermal state,*

1. Introduction

Many researches show us that approximately 25 % energy produced by a combustion process is lost to the engine cooling system [1]. In order to increase the piston engine effectiveness, we should recognize the heat-releasing phenomenon from an engine cylinder volume. The knowledge makes it also possible to determine thermal stresses in particular elements of cylinder, as well as to model emission of toxic compounds contained in exhaust gas [2].

It is necessary to express that working features of piston engines, for example cyclic changes of combustion process parameters depended on crankshaft positions, can cause to additional difficulties in describing such a process in appropriate quantitative and qualitative way. Therefore, in order to identify the amount of heat lost, we should determine not only parameters occurring in the combustion chamber and cooling volume, but also geometrical features (sizes and shapes) of a cylinder liner. Additionally, it should be stressed that structural elements of engine cylinders are massive units with complex shapes and – in the case of marine engines – of large dimensions as they have to withstand large mechanical and thermal loads. For this reason, they are capable of accumulating a large amount of heat energy, which may cause detrimental effects such as thermal overloading which – in extreme cases – may result in engine failures.

The presented work has been aimed at developing a multi-dimensional model of heat conduction through structural elements of piston engine cylinder, with a use of one of the numerical methods of solving heat conduction problems, namely the radiosity method [3]. Such a model has been applied to visualize temperature distribution of the mentioned components for the laboratory two-stroke engine installed in Gdynia Maritime University.

2. Modeling of the heat transfer coefficient

The heat transfer rate from the combustion gases to the combustion chamber wall is usually expressed by the Newton's law [4]. It uses, *inter alia*, the term of the experimental heat transfer coefficient. Many models proposed various ways to obtain such a coefficient. They assumed that the heat flux is the same for all surfaces in construction elements of the engine combustion chamber.

First of them is Nusselt's model [5]. It assumed steady state heat transfer and shows dependence of amount of the heat transfer coefficient on the mean piston speed, the temperature difference, the cylinder gas pressure and a gas and the wall emissivity. Based on the same parameters, Sitkei [6] proposed a different experimental equation for four-stroke, indirect injection diesel engines. Eichelberg [5] proposed very simple model for two and four-stroke engines and Hohenberg studied the heat transfer for six engine types [7]. Wiebe's proposal presented in [8], makes a value of the overall heat-transfer coefficient dependent on geometrical sizes of a cylinder volume, average speed of a piston, and stage parameters of a mixture averaging for the total volume of a cylinder space. A value of such a coefficient changes according to the crankshaft position. Woshni proposes the similar dependency in [9]. He developed it adding variable coefficients, which vary with different phases of the engine cycle. Annand cited in [10] proposed other approach. He determined amount of heat transferred to cylinder walls by means of adding heat conveying trough the convection and radiation phenomena. However, he made the accuracy of results received with using of this method dependent on the correct determination of so-called calibrating constants. As a rule, these constants can be obtained by means of laboratory tests. The presented correlation dependencies can be helpful in setting up the total energy balance of piston engines because they require only a small number of the input data. Nevertheless, the accuracy of results received in this way depends on calibrations made every time for the specific engines. The comparison of values of the heat-transfer coefficients determined for a laboratory engine by using the described methods is presented in [11]. Results received by these methods have the sufficient discrepancy, reaching almost 80% for beginning and throughout of a combustion process. However, the mentioned dependencies describe only the overall heat quantity transferred from the cylinder liner or the whole engine and they are not able to describe the local and transient flow of heat [12].

Therefore, they are not suitable to describe thermal stages of structural components of an engine cylinder. In last years, models describing of the multidimensional flow of heat through cylinder walls have been developed according to the progress made in the field of the turbulent combustion of fuel. It is obvious that these models take into consideration the changeable conditions of a combustion process in various points of a cylinder volume.

3. Heat transfer through construction elements of the engine

Construction elements of the cylinder of large marine two-stroke engine have usually cylindrically shapes. Therefore, in this case use of the cylindrical arrangement of equations is more adequate. The heat flow balance for an elementary geometrical area of engine cylinder structural element (Fig.1) can be presented as energy balance as follows:

$$Q_V + \sum_{i=1}^{n} Q_i = 0, \tag{1}$$

where:

Q_V – an internal heat source,
Q_i – amount of heat flow from a neighboring elementary geometrical area,

n – a number of neighboring areas.

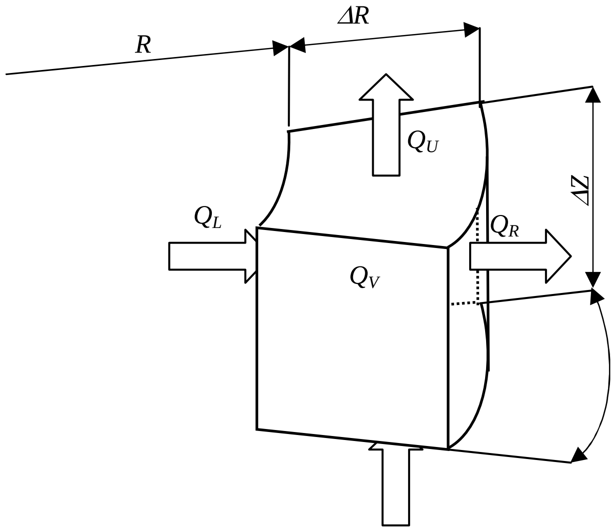


Fig 1. An elementary volume of a cylinder liner structural component

According to Fourier's law of heat transfer, the heat flux is proportional to the local temperature gradient in any direction:

$$Q = -\lambda \cdot \nabla T \ , \tag{2}$$

where:

λ – thermal conductivity of material [W/(m·K)],
∇T – temperature gradient [m·K].

Assuming that properties of structural material are isotropic in all directions, we can state that there is no heat source inside the considered area and the heat exchange process is stationary. The heat flux across walls of the elementary component can be presented by the following equations:

$$Q_{V \Rightarrow U} = \left(R + \frac{\Delta R}{2} \right) \Delta R \cdot \Delta \varphi \cdot \lambda \left(\frac{T_V - T_U}{\Delta Z} \right), \tag{3}$$

$$Q_{V \Rightarrow R} = \left(R + \Delta R \right) \Delta Z \cdot \Delta \varphi \cdot \lambda \left(\frac{T_V - T_R}{\Delta R} \right), \tag{4}$$

$$Q_{D \Rightarrow V} = \left(R + \frac{\Delta R}{2} \right) \Delta R \cdot \Delta \varphi \cdot \lambda \left(\frac{T_D - T_V}{\Delta Z} \right), \tag{5}$$

$$Q_{L \Rightarrow V} = R \cdot \Delta Z \cdot \Delta \varphi \cdot \lambda \left(\frac{T_L - T_V}{\Delta R} \right), \tag{6}$$

where:

T – temperature [K],
$_{L,\,R,\,U,\,D}$ – indexes of neighboring areas temperatures (see Fig. 1),
λ – thermal conductivity of material [W/(m·K)].

Substituting of Eq. (3) to Eq. (6) and next into Eq. (1) and taking into account that $\Delta Z = \Delta R = X$, we obtained the following relation:

$$T_V = \frac{1}{4}T_U + \frac{1}{4}T_D + \left(\frac{R+X}{4R+2X}\right)T_R + \left(\frac{R}{4R+2X}\right)T_L, \tag{7}$$

Eq. (7) for modeling of heat flow through an engine cylinder liner could not give correct results due to the unstable heat transfer through the cylinder liner structural components resulting from the cyclic engine work. Moreover, thermal energy accumulation in the cylinder liner structural components complements such a kind of phenomena. In this case, we converted the Eq. (1) to the following form:

$$Q_{D\Rightarrow V} - Q_{U\Rightarrow V} - Q_{R\Rightarrow V} + Q_{L\Rightarrow V} = Vol \cdot c_p \cdot \rho \cdot \frac{T_V^{+1} - T_V}{\Delta t}, \tag{8}$$

where:

Vol – volume of the elementary component [m^3], equals $\left(R + \frac{1}{2}\Delta R\right)\Delta R \cdot \Delta\varphi \cdot \Delta Z$,

c_p – specific heat at constant pressure[J/(kg·K)],
ρ – density of the elementary control volume [kg/m^3],
Δt – considered time interval [s],
T_V^{+1} – temperature after Δt time [K].

Using the notion of the Fourier discrete number ΔFo for two-dimensional heat flow [13] inside elementary area, we can express the temperature T_V^{+1} by the following equation:

$$T_V^{+1} = T_V(1 - 4\Delta Fo) + \Delta Fo\left(T_U + T_D + T_R\frac{R+X}{R+0.5\cdot X} + T_L\frac{R}{R+0.5\cdot X}\right), \tag{9}$$

where:

ΔFo – the Fourier discrete number [–], equals $\frac{\lambda \cdot \Delta t}{c_p \cdot \rho \cdot X^2}$.

In the iterative solutions, the steady-state condition should be met. It can be expressed by the following inequality:

$$\Delta Fo > \frac{1}{4}, \tag{10}$$

4. A model of temperature in the engine construction elements

The input data for a thermal state model are the boundary conditions on borders of the cylinder liner structural components and initial conditions determined by means of the experimental measurements or modeling of a combustion process in the cylinder volume. Both the boundary and the initial conditions determine a thermal state for structural component boundaries. All calculations were carried out for the one-cylinder, two-stroke, and crosshead laboratory engine with the straight-through scavenging. The fresh water flowing through the wet cylinder liner cools its cylinder volume. The main parameters of this engine are; the piston stroke 350mm, a diameter of the cylinder 220mm, the actual rotational speed 200 rpm and the actual power output 17kW. The structural similarity to the large-size marine engines was the reason of its selection as the modeling item. Using design documentation of the mentioned engine, we have divided the cylinder liner structural components into the elementary components with a size 2 mm of their sides (parameter *X* in relative Equations). Taking into mind axial-symmetrical shapes of the modeled elements, we limited our modeling to the two-dimensional areas located in the longitudinal section. These elementary control patches allow us to describe the temperature field for the following components: the engine piston together with its rings considered as the uniform structural component, the cylinder liner, the cylinder block with under-piston chamber and the cylinder head together with its exhaust valve and injector.

For describing the heat exchange phenomena, the following forms of boundary conditions were applied:

– Dirichlet’s conditions for a surface between the structural component walls and the surrounding air, which were obtained by determination of the wall temperature equals to the air temperature measured during the experimental study,
– Dirichlet’s conditions for a surface of under-piston chamber which were obtained by calculation of compression in this area during the engine working [14],
– Fourier’s condition for a surface between the structural component walls and the cooling volume,
– Fourier’s condition for a surface between the structural component walls and the combustion chamber.

The Fourier boundary condition was obtained with the use of heat transfer coefficients, which are calculated individually for local conditions. The convective heat transfer coefficient was determined by the following semi-empirical equation:

$$\alpha_C = 0{,}023 \cdot \left(\frac{C \cdot X}{\nu} \right)^{0,8} \cdot \left(\frac{c_{pa} \cdot \nu}{\lambda_a} \right)^{0,4} \cdot \frac{\lambda_a}{X}, \qquad (11)$$

where:

C – speed of gas in a combustion chamber assumed as a mean piston speed or mean speed of water in a cooling volume, calculated by Poiseuille formula [m/s],
ν – a kinematic viscosity [m^2/s], assumed $\nu = 6 \cdot 10^{-11} \cdot T^2 + 7 \cdot 10^{-8} \cdot T - 1 \cdot 10^{-5}$ for gas in a cylinder and $8{,}60 \cdot 10^{-5}$ m^2/s for the cooling water,
λ_a – thermal conductivity of material [W/(m·K)], assumed $\lambda = -2 \cdot 10^{-8} \cdot T^2 + 8 \cdot 10^{-5} \cdot T + 0{,}0037$ for gas in a cylinder and 0,612 W/m·K for the cooling water,
c_{pa} – specific heat at constant pressure[J/(kg·K)], assumed $c_p = 3 \cdot 10^{-7} \cdot T^2 + 0{,}1974 \cdot T + 938{,}14$ for gas in a cylinder and 4178 J/kgK for the cooling water.

The radiative heat transfer coefficient determined on the basis of Newton’s and Stefan-Boltzmann’s laws can be described as follows:

$$\alpha_{Ri} = \frac{\varepsilon \cdot C_C}{T_i - T_V} \left(T_i^{\,4} - T_V^{\,4} \right), \qquad (12)$$

where:

ε – a relative emissivity determined for „grey” flame and „lusterless” surface of cylinder walls equals ε=0,79,
C – a Stefan-Boltzmann’s constant, equals Cc= 5,67·10^{-8} W/(m^2·K^4),
T_i – a temperature of a combustion chamber and a local temperature in the cooling volume [K].

The sum of convective and radiative heat transfer coefficient was take into account to describe Fourier’s condition for surfaces. The correct value of T_V temperature of elementary area was obtained by using the iterative method, whereas the input data regarding temperature T_i in a combustion chamber were taken from the combustion process model presented in [14].

5. Results of modeling

Solving Eq. (9) for each of elementary control patches, we can obtain a temperature field picture for cylinder components in cylindrical arrangement. All necessary calculations we performed for the described laboratory engine. The engine thermodynamic state varied according to its crankshaft position angle. It is represented by changes of temperature in a combustion chamber. Values of these temperatures are presented in [15]. Taking it into account, we carried out calculations beginning from the angle equal 8º before and ending at 88º after the top dead centre (TDC). Moreover, we performed these calculations in interval 8º, what gave the time interval of 6 [ms] at the set rotational speed. Using of such intervals together with the assumed sizes of elementary components allowed us to meet the condition expressed by Eq. (10). This, in turn, ensured the convergence of several iterative solutions. Bearing in mind the unstable character of this heat transfer, we applied the input data in the form of a temperature field resulting from the previous crankshaft position in order to calculate temperatures of cylinder liner structural components. Only the starting calculations for an angle 8º before TDC, we carried out with using Equation (7) assuming the steady heat transfer.

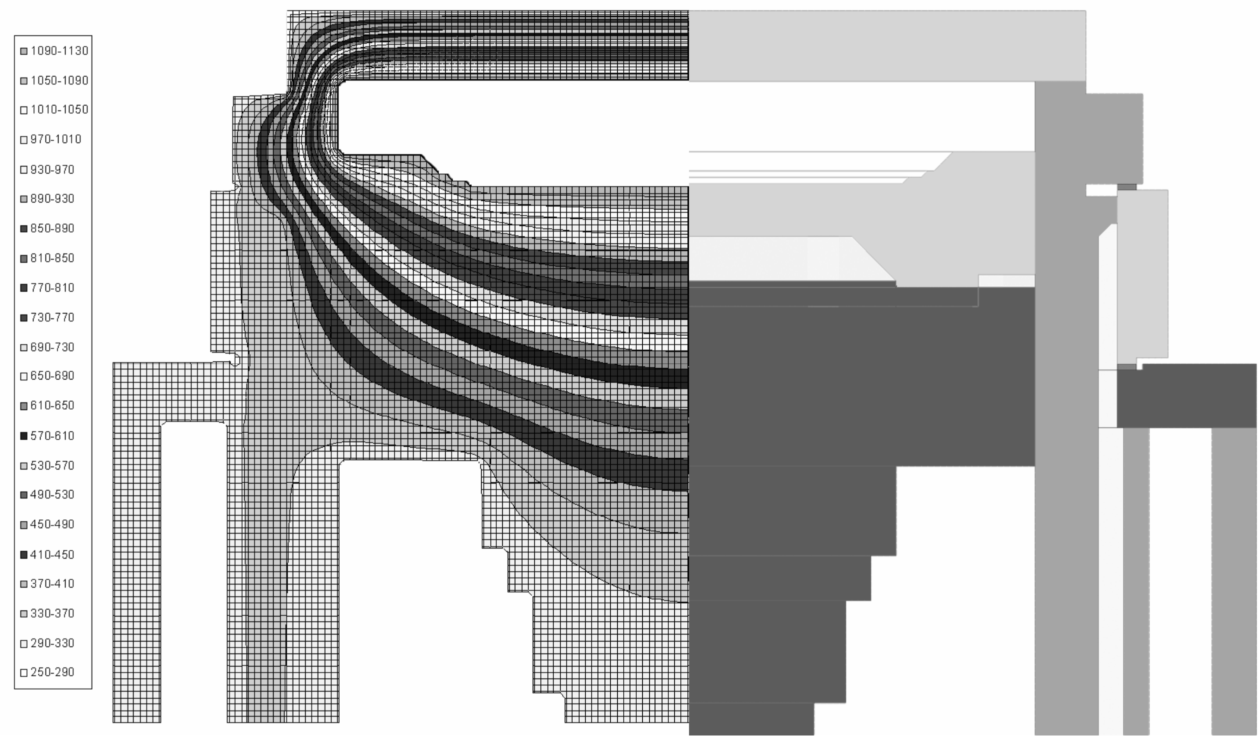
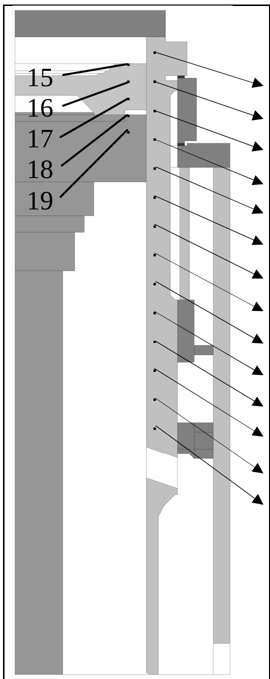


Fig 2. The example of temperature field in engine structural components shown in axial cross-section (left side) and schematic view of an upper part of the engine cylinder (right side)

In the left side of Fig. 2, the example of modeling results is presented in the form of the temperature field of engine structural components shown in axial cross-section. Due to the large number of elementary areas, the obtained modeling results are presented in the form of multi-color map. Borders of particular colors correspond with the isotherms dividing the cylinder construction areas into the temperature intervals of 40 K. The right side of Fig. 2 presents the schematic axial cross-section of engine cylinder construction applied in modeling the temperature field within particular structural compo nets.

Depiction of the modeled cylinder in its longitudinal section and temperatures of its structural components are presented in Table 1. The distinguished points plotted on its individual structural components are related to layouts of the elementary components for which of temperature values were calculated. Based on these results, we observed considerable differences of temperatures between furthest geometrical points of the cylinder reaching even 820 K, but in one point differences of temperatures did not exceed 12 K (point 2). It resulted from thermal inertia of construction components represented by the Fourier discrete number *ΔFo*. High temperature in upper side of cylinder elements is observed. The reason of this fact is modeling of temperature in start of combustion process by using Eq. (7), without considering a thermal inertia of cylinder construction components.

Tab. 1. The modeled cylinder and temperatures of its structural components



Number of comp.	Temperature [K] in elementary components in crankshaft position												
	-8º	0º	8º	16 º	24 º	32 º	40 º	48 º	56 º	64 º	72 º	80 º	88 º
1	861	861	861	861	861	865	865	865	865	865	865	865	865
2	638	638	638	638	638	640	640	640	640	640	640	640	640
3	455	455	455	455	455	456	456	456	456	456	456	456	456
4	386	386	386	386	386	387	387	387	387	387	387	387	387
5	342	342	342	342	342	342	342	342	342	342	342	342	342
6	316	316	316	316	316	316	316	316	316	316	316	316	316
7	314	314	314	314	314	314	314	314	314	314	314	314	314
8	314	314	314	314	314	314	314	314	314	314	314	314	314
9	313	313	313	313	313	313	313	313	313	313	313	313	313
10	307	307	307	307	307	307	307	307	307	307	307	307	307
11	302	302	302	302	302	302	302	302	302	302	302	302	302
12	301	301	301	301	301	301	301	301	301	301	301	301	301
13	301	301	301	301	301	301	301	301	301	301	301	301	301
14	301	301	301	301	301	301	301	301	301	301	301	301	301
15	1119	1122	1121	1121	1120	1120	1119	1119	1118	1118	1117	1117	1116
16	894	894	894	894	894	895	895	895	895	895	895	895	895
17	720	720	720	720	720	721	721	721	721	721	721	721	721
18	595	595	595	595	595	596	596	596	596	596	596	596	596
19	504	504	504	504	504	505	505	505	505	505	505	505	505

6. Conclusions

The presented paper deals with a model of heat transfer through structural components of the engine cylinder. Results obtained during modeling allowed us for the qualitative estimation of a thermal state of the engine cylinder. Nevertheless, the lack of experimental verification does not permit to carry out the quantitative estimation of such a state. Moreover, simplification made in representation of a cylinder structure within the piston and cylinder head makes impossible to obtain the high accuracy of such a modeling. Therefore, in order to increase the model adequacy, we should increase an accuracy of representation of a structure of the considered areas by means of modeling friction nodes: a piston - piston rings - a cylinder liner. It, in turn, entails the necessity to decrease geometrical sizes of elementary control patches. The modeled temperature in certain points seems to be too high. The reason of this fact probably is modeling of temperature in start of combustion process without considering a thermal inertia of components. In order to remove this problem, modeling of temperature of elements should be begin from start of compression process. The obtained modeling results may contribute to an increase of modeling accuracy of the phenomena occurring within the engine combustion chamber, accompanied by a significant decrease of the modeling cost associated with using special computer software. Such a model makes possible to develop guidelines for designing of the engine cylinder structure taking into account decreasing of thermal stresses by optimization of temperature distribution in the cylinder components. As far as combustion process models are concerned, the modeling of temperature distribution within cylinder walls may effectively contribute to an increase of engine efficiency – on the one hand – due to the decrease of total heat flowing out to the engine cooling space and – on the other hand – due to the possibility of forming the heat flow in complex areas of a cylinder space. Moreover, the obtained results may be used in teaching the subjects associated with combustion engines, i.e. analysis of thermal stresses and temperature distribution within engine elements.

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