The thermal state modelling of cylinder liner of marine two-stroke combustion engine

Jerzy Kowalski
Wiesław Tarełko
Gdynia Maritime University

ABSTRACT

This paper presents a two-dimensional model of heat flow through structural elements of cylinder of two-stroke cross-head engine of longitudinal scavenging, obtained with the use of the elementary balance method. Special attention was paid to the modelling of temperature distribution within engine cylinder liner of „wet" construction. For modelling the unsteady heat flow multi-dimensional equations with Dirichlet - - Fourier boundary conditions, were used. For the Fourier boundary conditions in the engine cylinder space local values of convective and radiant heat-transfer coefficients were applied. For calculations the KM3R method of solving differential equations, based on the elementary balance method, was used. Modelling results have been presented in the form of the temperature field of engine cylinder structural elements in function of the changeable angle of crankshaft position.

Key words : ship engine, elementary balance method, thermal state, cylinder liner

INTRODUCTION

For the last several ten years piston engines have become one of the most important sources of ship powering. Hence permanent interest paid to increasing their efficiency seems justified. The main source of energy loss in piston engine is the heat flow from engine cylinder space to cooling liquid. It is estimated that about 25% of the energy produced in fuel combustion process is lost to cooling system [1]. In order to increase piston engine efficiency knowledge of the process of heat flow-out from its cylinder space is necessary. 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].

The process of heat flow-out from engine's combustion chamber to its cooling system is very complex and dependent on many factors. The following, for instance, can be numbered among them [3] :

- properties of media taking part in combustion process, as well as properties of materials of combustion chamber elements (density, specific heat, emissivity)
- combustion process parameters (temperature, pressure, media flow velocity)
- gas flow velocity distribution within combustion chamber, dependent on run of combustion reaction.

For quantitative and qualitative description of the process additional complications arise from the specific character of piston engine work, consisting in cyclic changes of the above mentioned parameters, depending on crank angle position.

Hence, in order to identify a heat amount lost this way, to determine not only parameters which control the processes in combustion chamber and cooling space but also geometrical features (dimensions, shape) of engine cylinder, is necessary. Additionally, it should be stressed that structural elements of engine cylinders are massive units of a complex shape and – in the case of ship engines – of large gabarites as they have to withstand large mechanical and thermal loads. For this reason they are capable of accumulating a large amount of heat energy, that may cause detrimental effects such as thermal overloading which – in extreme cases – may result in engine failures.

The presented work has been aimed at building a multi-dimensional model of heat conduction through structural elements of piston engine cylinder, with the use of one of the numerical methods of solving heat conduction problems, namely the elementary balance method [4]. In this work a spreadsheet was applied to numerical solving the problem. The derived model was used for imaging the temperature distributions within elements of a laboratory two-stroke cross-head combustion engine.

The obtained modelling results may contribute to an increase of modelling accuracy of the phenomena occurring within engine cylinder space, accompanied by a significant decrease of the modelling cost associated with using a special computer software. Owing to this there is a possibility to elaborate guidelines for designing the engine cylinder structural elements to make thermal stresses lowering by optimization of temperature distribution in the elements possible. As far as combustion process models are concerned the modelling of temperature distribution within cylinder walls may effectively contribute to an increase of engine efficiency – on the one hand – due to a decrease of total heat flowing out to engine cooling space and – on the other hand – due to possibility of forming the heat flow in trouble areas of cylinder space. Knowledge of heat flow-out to cooling liquid in some areas of cylinder space may also contribute to a reduction of emission of toxic compounds contained in exhaust gas e.g. by limitation of the phenomenon of „freezing" nitric oxides on cylinder walls. Moreover the achieved results may be used in teaching the subjects associated with combustion engines, a.o. analysis of thermal stresses and temperature distribution within engine elements.

MODELLING THE HEAT CONDUCTION THROUGH ENGINE CYLINDER LINER

For a few dozen years have been carried out the investigations dealing with a way of comprehensive expressing the phenomenon of heat transfer between combustion chamber and cooling system. Beginning from the late 1970s efforts of many research teams aware of complexity of the problem, have been focused on elaboration of empirical relationships for determination of an overall heat-transfer coefficient which could be applied to description of amount of cooling heat in accordance with Newton law [5].

The relationship proposed by Wiebe [6], makes values of the heat-transfer coefficient dependent on geometrical dimensions of cylinder space, mean piston speed as well as on mixture state parameters averaged over entire cylinder space. The coefficient's value varies along with the crank angle position. The similar relationship, but enriched by some factors changeable for different engine cycle phases, has been proposed by Woshni [7].

Another approach has been proposed by Annand referred to e.g. in [8], who has determined the amount of heat transferred to cylinder walls by adding the heat resulting from convection and radiation. The author has made correctness of so obtained results dependent on correct determination of three empirical calibration constants.

All the mentioned correlation relationships and other similar ones are very useful in elaborating the overall engine energy balance. They are popular in use as they require a very small number of input data, however correctness of obtained this way results is dependent on their calibration for a given testing object. A comparison of values of heat-transfer coefficients calculated for a laboratory combustion engine can be found in [3].

The obtained results showed very great differences in values derived from the above mentioned methods, reaching even about 80% for the parameters in the instant close to the beginning of combustion process and its run. It should be added that the above mentioned correlative relationships describe total amount of cooling heat transferred from a cylinder or entire engine and they are not able to describe any local and unsteady heat flow [9].

For this reason such relationships are not sufficient for describing thermal state of particular structural elements of engine cylinder. Along with the developing of research on turbulent fuel combustion in cylinder space, models for describing multi-dimensional heat flow through cylinder walls with accounting for changeable conditions of combustion process in various areas of cylinder space, appeared necessary.

Unfortunately, numerical calculations of combustible mixture velocity and temperature fields within cylinder space require so large computation capacity that the heat exchange processes must be usually subjected to significant simplifications. The simplest and often used trick is to reduce amount of combustion heat by 30-40%, within boundary layer.

For qualitative and quantitative determination of heat exchange between media filling engine's cylinder space during combustion process and cooling liquid it is necessary not only to know the heat transfer process to and from cylinder walls, but also how the heat is conducted through structural elements of engine cylinder. The isotropic thermodynamical properties of structural materials used for engine building make the problem much simpler. However a complex shape and large gabarites of those elements make application of multi-dimensional modelling necessary.

HEAT TRANSFER WITHIN STRUCTURAL ELEMENTS OF ENGINE CYLINDER

The heat flow balance for an elementary geometrical area of engine cylinder structural element (Fig.1) can be presented as follows :

$$Q_V + \sum_{i=1}^{n} Q_i = 0 \qquad (1)$$

where :

Q_V – internal heat source
Q_i – heat flow from a neighbouring elementary geometrical area
n – number of neighbouring areas (n = 6 for three-dimensional system, n = 4 for two-dimensional system).

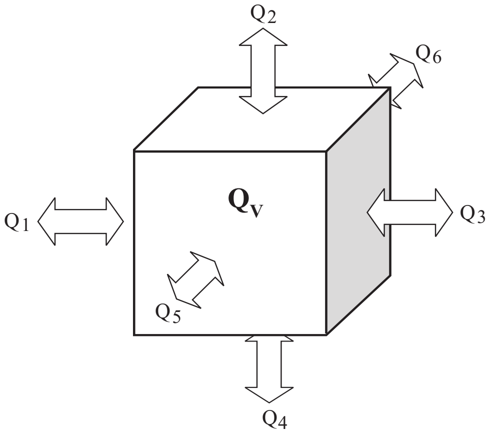


Fig.1. *Elementary geometrical area*

In compliance with Fourier's heat conduction law, the heat flows Q_i are directly proportional to local temperature gradient. For the elementary geometrical area (Fig.1) the temperature gradient can be described by the following equation :

$$\frac{\partial T(x,y,z,t)}{\partial t} = \frac{\lambda}{c_p \rho}\left[\frac{\partial^3 T(x,y,z,t)}{\partial x^3} + \frac{\partial^3 T(x,y,z,t)}{\partial y^3} + \frac{\partial^3 T(x,y,z,t)}{\partial z^3}\right] \qquad (2)$$

where :

T – temperature of elementary geometrical area
x, y, z – dimensions of elementary geometrical area
t – considered time interval
λ, c_p, ρ – conductive heat coefficient, specific heat and density of elementary geometrical area, respectively.

On the assumption that :

- ➔ properties of structural material are isotropic in all directions
- ➔ shape of the elementary geometrical area is cubical
- ➔ there is no heat source inside the area, and
- ➔ heat exchange process is stationary,

the equation (2) has the solution of the following form :

$$T_V = \frac{\sum_{i=1}^{n} T_i}{n} \qquad (3)$$

where :

T_v – temperature of elementary geometrical area
T_i – temperatures of neighbouring areas.

For the above mentioned assumptions, the mean arithmetic temperature, taken from the neighbourhood of the considered elementary geometrical area, is the solution of Eq. (2). Application of the equations in the form (3) to modelling would not provide any correct results because of a non-stationary character of heat flow through engine cylinder structural elements. The heat flow variability results from engine cyclic work associated with reciprocating motion of engine piston. This is connected with heat energy accumulation in cylinder structural elements, causing cyclic changes of internal energy of the elements. Using the notion of the Fourier discrete number, ΔFo, for one-dimensional heat flow [10], expanded to the three-dimensional form for elementary cubical area :

$$\Delta Fo\,(x\,,\,y,\,z)=\frac{\lambda\,\Delta t}{c_p\,\rho\,(x,\,y,\,z)^3} \tag{4}$$

one can determine a temperature value of elementary cubical area by means of the solution of Eq. (2) in the following form :

$$T_{V(t+1)}=T_{V(t)}\left(1-n\,\Delta Fo\right)+\Delta Fo\sum_{i=1}^{n}T_i \tag{5}$$

By making use of Eq. (5), to describe the spatial temperature field within engine's cylinder structural elements at assumed finite dimensions of elementary geometrical areas is possible. Application of an iterative solving method makes it possible to fast obtain results under fulfillment of the stability condition for iterative solution, described by the following relationship :

$$\Delta Fo>\frac{1}{n} \tag{6}$$

THERMAL STATE MODELLING OF CYLINDER LINER

The below described conditions on the boundaries of structural elements, as well as the initial conditions determined by direct measuring and modelling the combustion process within cylinder space, were taken as input data. Thermal state at boundary of a structural cylinder element is determined by the mentioned boundary and initial conditions. An advantage of the elementary balance method is the possibility of use of various forms of the boundary conditions depending on location of a given element within engine structure.

Thermal state of cylinder liner, understood as a multi-dimensional representation of temperature field within cylinder liner, was modelled as a result of iterative solving process of the equations in the form of Eq. (5). As the investigated object was chosen a one-cylinder, two-stroke, cross-head combustion engine with longitudinal scavenging and cylinder space cooled with fresh water through cylinder liner of „wet" construction. The main parameters of the engine are presented in Tab.1.

***Tab. 1.** Main parameters of the investigated laboratory combustion engine .*

Parameter	Symbol	Unit	Value
Piston stroke	S	[mm]	350
Cylinder diameter	D	[mm]	220
Max. rotational speed	N	[rpm]	600
Max. power output	P	[kW]	73.5

Choice of the engine was based on the similarity of its construction to that of large combustion engines used for ship propulsion. On the basis of its design drawings structural elements of the engine were divided into elementary geometrical areas. The modelling was limited, because of axially symmetrical form of the elements, to a two-dimensional area located in axial cross-section with application of 5 mm x 5 mm square elementary areas. Five thousand of the so derived elementary areas made it possible to describe the temperature field of the following structural elements of engine cylinder (in the axial cross-section) :

- the engine's piston together with its rings – as an uniform element
- the cylinder liner - from its upper edge to the upper edge of inlet ports
- the cylinder body up to the height of the upper edge of inlet ports
- the cylinder head together with the exhaust valve and injector up to the height of four elementary areas.

The schematic diagram of the modelled engine cylinder area is presented in Tab.2.

For iterative solving the temperature field the KM3R calculation method [11] was used. It makes it possible to fast and effectively describe the heat flow phenomena by finite difference equations and to solve them by using a spreadsheet. The application of the KM3R method enables to fast modify the equation of the same form as (5), which consists in supplementing it with the boundary conditions obtained by replacing the temperature T_i with the equation describing the considered temperature by an arbitrary boundary condition.

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

- the Dirichlet condition (also called the 1st kind condition) – at the contact of walls of engine cylinder structural elements with the air surrounding the engine – by using the temperature of cylinder walls equal to air temperature measured during laboratory tests
- the Fourier condition (also called the 3rd kind condition) – at the contact of walls of engine cylinder structural elements with cooling water – with application of the convective heat - transfer coefficient determined for the entire water jacket
- the Fourier condition of 3rd kind – at the contact of walls of engine cylinder structural elements with cylinder space – – with application of convective and radiant heat-transfer coefficients individually calculated for each elementary area on the basis of actual conditions in cylinder space resulting from combustion process (influence of chemical reactions during combustion process on heat flow was neglected)
- the contact condition of 4th kind – at the contact of particular structural elements – with application of contact thermal resistance globally determined for all the elements.

Influence of the phenomena describing the heat flow from cylinder space to cylinder walls [12], on the obtained results, is prevailing. For this reason the heat-transfer coefficients for the elementary areas being edges of engine's structural elements neighbouring to cylinder space, were individually determined on the basis of local conditions. Realization of the Fourier boundary condition was made with the use of the Biot's number described as follows :

$$Bi=\frac{\left(\alpha_{Ci}+\alpha_{Ri}\right)\Delta x}{\lambda} \tag{7}$$

where :

α_{Ci} – convective heat-transfer coefficient determined on the basis of local Nusselt number

α_{Ri} – radiant heat-transfer coefficient determined on the basis of Newton's and Stefan-Boltzmann's laws, and described as follows :

$$\alpha_{Ri} = \frac{\varepsilon C}{T_i - T_V}\left(T_i^4 - T_V^4\right) \qquad (8)$$

where :

ε – relative emissivity determined for „grey" flame and „lustreless" surface of cylinder walls under assumption on fulfillment of Lambert's law

C – Stefan-Boltzmann's constant.

A correct value of T_V temperature of elementary area, determined from Eq. (5) with accounting for Eq. (7) and (8), was obtained by using the iterative method, whereas input data regarding temperature in cylinder space were taken from the combustion process model presented in [13] and [14].

RESULTS OF MODELLING

The solution of the equations in the form of Eq. (5), for each of the elementary geometrical areas, provided an image of the temperature field in the axial cross-section of the engine cylinder. The calculations were performed for the engine's rotational speed of 200 [rpm] and load equal to about 93% of its rated output. They were commenced beginning from the crank angle position equal to 5° before the top dead centre of piston (TDC) because of the thermodynamical conditions changing along with crank angle position. Up to the angle of 10° behind the TDC the calculations were made at every 5° interval , that gave the time interval of about 4 [ms] at the set rotational speed. The used time scale together with the assumed dimensions of elementary areas made it possible to satisfy the condition (6), which resulted in ensuring the convergence of series of iterative solutions. As the starting point of fuel injection to the engine in question was set at 7° angle before the TDC, hence for the piston positions corresponding with the crank angle greater than 10° behind the TDC the calculations were performed at every 10° interval. Taking into account the unsteady character of heat flow, for temperature calculations of elementary areas of engine cylinder structural elements at a given crank angle position, one used the input data in the form of the temperature field derived from the calculations for the preceding crank angle position. Only initial calculations for the angle of 5° before the TDC were made with the use of Eq. (3) under assumption of steady heat flow.

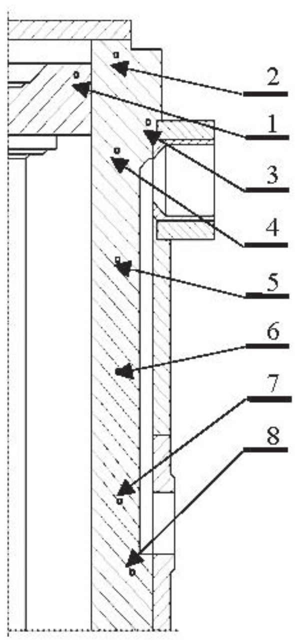
Tab.2 presents the schematic axial cross-section of engine cylinder construction applied in modelling the temperature field within particular structural elements. The points marked on the scheme correspond with the location of the elementary geometrical areas for which the temperature values derived from the modelling are presented.

In Fig.2 the modelling results are presented in the form of the temperature field of engine structural elements shown in axial cross-section. Because of the large number of elementary areas the obtained modelling results are presented in the form of multi-colour map on which the borders of particular colours correspond with the isotherms dividing the cylinder construction areas into the temperature intervals of 50 [K].

The results presented in Fig. 2 show a very changeable character of the cylinder liner temperature field, that results in the variable values and directions of heat flows. Worth mentioning, that the presented results cover only about 67 [ms] of engine working time. On the basis of the analysis of the results given in Tab.2, large temperature differences, reaching 1100 [K], between extreme geometrical points of the cylinder liner, can be stated. According to Fourier law, such situation generates intensive heat flow towards the engine cylinder axis. It makes rationality of application of one-directional heat flow models to modelling the heat flow through structural elements of marine large combustion engines, questionable. The above mentioned temperature differences amount to a few hundred [K] even at the crank angle of 90° when the temperature in the combustion chamber is relatively low.

The spatial modelling of heat flows may be a very useful tool for the assessment of structural correctness of a cylinder liner. As results from Fig.2, the areas of the modelled cylinder liner of the laboratory engine, located in its upper part are

Tab. 2. *Temperature modelling results for elementary geometrical areas located in the characteristic points of engine cylinder construction, denoted by Arabic numerals .*

	Crank angle position [°]	Cylinder space temperature [K]	Elementary geometrical areas							
			1	2	3	4	5	6	7	8
			Temperature [K]							
	-5	1612	1398	992	405	381	305	303	303	303
	TDC	1823	1498	993	406	381	305	303	303	303
	5	1315	1398	992	405	381	305	303	303	303
	10	779	706	577	343	337	304	303	306	306
	20	733	669	570	361	373	304	303	306	306
	30	722	662	573	406	494	308	303	306	306
	40	722	662	574	442	621	328	304	306	306
	50	719	659	573	451	635	462	305	306	306
	60	713	653	569	450	632	617	335	306	306
	70	711	651	568	449	631	625	534	313	307
	80	704	646	564	447	625	620	613	412	317
	90	690	634	555	442	614	609	606	594	396

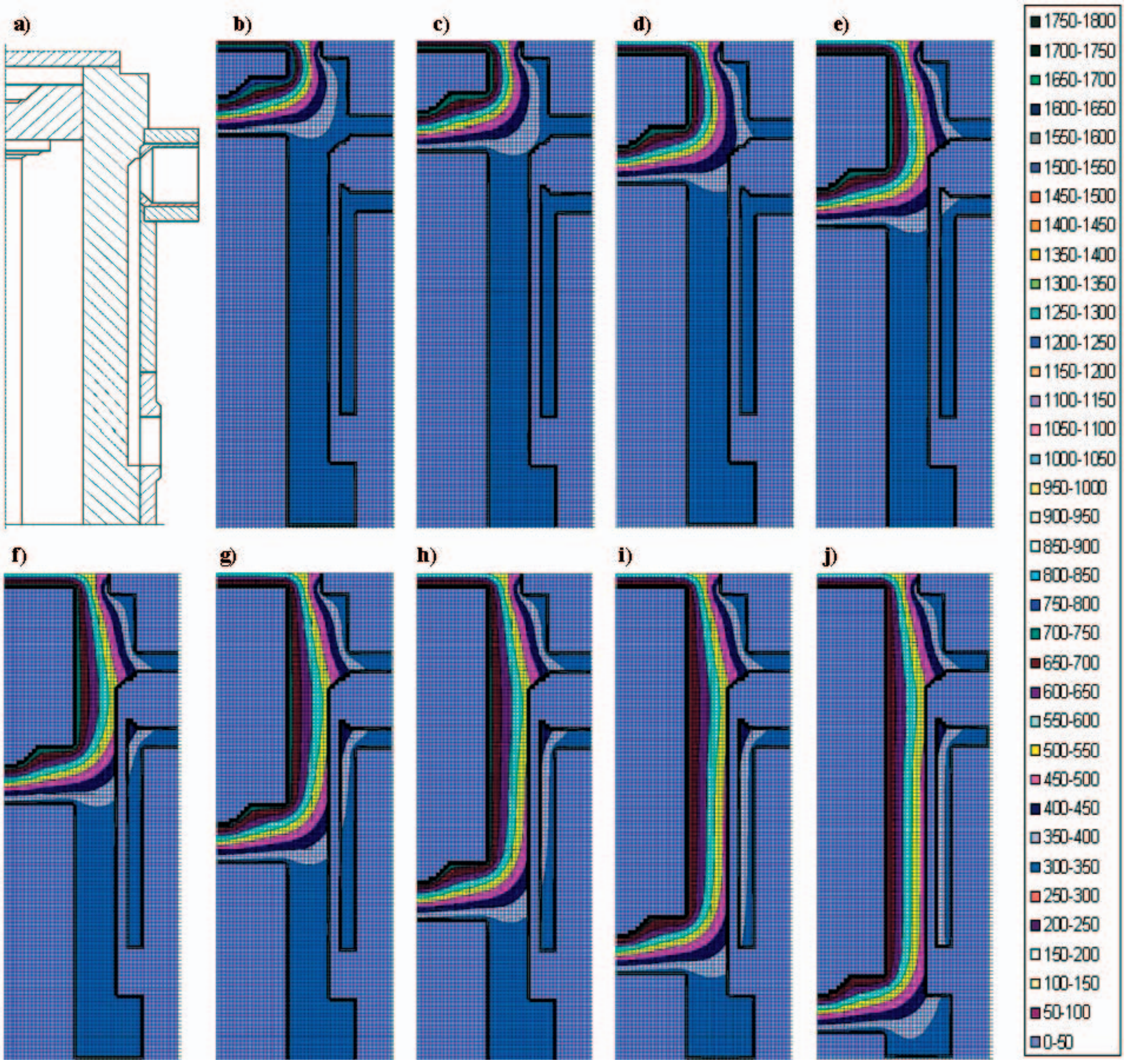


Fig. 2. *Temperature fields in the engine structural elements shown in axial cross-section, obtained as a result of the modelling for the engine rotational speed of 200 [rpm] and the load of about 93% of its rated output (temperature fields of the media flowing around the engine structural elements are not visible).* ***a)*** *right hand side half cross-section of schematic cylinder structure. Crank angles position after crossing the piston TDC, respectively :*

b) *– 10°* ***c)*** *– 20°* ***d)*** *– 30°* ***e)*** *– 40°* ***f)*** *– 50°* ***g)*** *– 60°* ***h)*** *– 70°* ***i)*** *– 80°* ***j)*** *– 90° .*

exposed to high temperatures. However, because of large heat accumulation in cylinder liner material, a significant temperature rise occurs in the area very close to water jacket, as late as at the crank angle reaches about 20°. In this time interval, fuel combustion process is already running through the instant corresponding with the crank angle displacement of 27°. In the case of two-stroke engine this angle corresponds with the period of burning the prevailing part of fuel charge, that results in production of large amount of thermal energy.

The presented design solution does not allow for transferring, to cooling system, that part of energy which is associated with the local heat flow in the vicinity of the elementary geometrical area No. 2 (Tab.2). According to the results presented in Fig.2, this area is very close to the air surrounding the engine, that leads to heat loss by natural convection.

As mentioned earlier, the thermal state model can make assessing the thermal stresses in cylinder liner possible. Such assessment is crucial for determining the displacements and places of potential structural failures, already in the stage of cylinder liner designing. In the present phase of investigations on the presented model it is not possible to unambiguously and strictly assess thermal stress state of cylinder liner. It is caused by the far-going simplifications introduced into the schematic representation of cylinder structure shown in Tab.2. In order to improve accuracy of modelling, a more strict representation of the structure, especially of the areas associated with fitting the piston rings, exhaust valve, injector as well as the inlet ports located beneath the modelled region, is necessary.

Strict representation of engine cylinder's structural elements of smaller dimensions was not possible because of the assumed too great size of particular elementary geometrical areas. For this reason as well as because of the lack of experimental verification of the obtained results they should be assessed only in the qualitative aspect but not quantitative one.

CONCLUSIONS

- The presented work was aimed at building the two-dimensional model of heat conduction within structural elements of engine's cylinder. The authors succeeded in building such model at little expense due to application of the KM3R method of solving differential equations, together with the elementary balance method.

- The obtained modelling results make qualitative assessing the thermal state of cylinder liner possible, however the present lack of their experimental verification does not allow to perform a quantitative analysis especially that aimed at determination of thermal stress state.

- Also, the simplifications introduced in representing the cylinder structure in the regions of piston and cylinder head, do not make it possible to achieve a high modelling accuracy. To improve adequacy of the model are necessary actions aiming at increasing the accuracy of representation of the engine construction in the considered areas by modelling the tribological unit of piston – piston rings – cylinder liner, which makes it necessary to decrease geometrical dimensions of elementary areas.

- Another important factor which influences the modelling accuracy is the application of the overall convective heat-transfer coefficients for water jacket of cooling system. However to increase in this way the modelling accuracy it is necessary to thoroughly analyze distribution of velocity of the cooling water flow through cylinder water jacket.

- However it seems that the presented model in the current form may serve as a basis for future research on heat conductance phenomena within structural elements of engine cylinder. The above specified actions aiming at improvement of the presented model adequacy may allow for its positive verification by means of laboratory measurements.

- The calculation method applied to solving the differential equations of energy balance makes it possible to use spreadsheet – a commonly available software – that greatly lowers cost of modelling.

- The simplicity of model solving makes it possible to use, also for educational purposes, the obtained results for simulation of thermodynamical phenomena occurring in the engine under operation.

NOMENCLATURE

C – Stefan-Boltzmann's constant
c_p – specific heat
n – number of neighbouring areas
Q_i – heat flow from a neighbouring elementary geometrical area
Q_v – internal heat source
t – considered time interval
T – temperature of elementary geometrical area
T_i – temperatures of neighbouring areas
T_v – temperature of elementary geometrical area
x, y, z – dimensions of elementary geometrical area

α_{Ci} – convective heat-transfer coefficient
α_{Ri} – radiant heat-transfer coefficient
ΔFo – increment of Fourier discrete number
ε – relative emissivity
λ, c_p, ρ – conductive heat coefficient, specific heat and density of elementary geometrical area, respectively

Indices

i – neighbouring elementary area
v – considered elementary area

ACRONYMS

KM3R – calculation method of solving differential equations
TDC – top dead centre of piston

BIBLIOGRAPHY

1. J. B. Heywood: *Internal Combustion Engine Fundamentals*. McGraw-Hill. 1988
2. Zhiyu Han, R. D. Reitz: *A temperature Wall function formulation for variable-density turbulent flows with application to engine convective heat transfer modelling*. Int. J. Heat Mass Transfer, Vol 40, No. 3. Elsevier Science. 1997
3. J. Ghojel, D. Honnery: *Heat release model for combustion of diesel oil emulsions in DI diesel engines*. Applied Thermal Engineering, Vol. 25. Elsevier Science. 2005
4. Kostowski E.: *Heat flow* (in Polish). Ed. I , Publications of Silesian University of Technology. 2000
5. F. P. Incropera, D. P. DeWitt: *Fundamentals of Heat and Mass Transfer*. Willey. 2001
6. H. Nguyen: *A simulation model of heat exchange in the ship diesel engine cylinder – environment system*. Polish Maritime Research No 1(31), Vol. 9. Gdańsk, 2002
7. G. Woschni: *An universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine*. SAE (Society of Automotive Engineers) paper No. 670931. SAE Trans. Vol. 76. 1967
8. J. B. Heywood, E. Sher: *The two-stroke cycle engine, its development, operation and design*. Taylor & Francis. Philadelphia, 1999
9. T. Rychter, A. Teodorczyk: *Mathematical modelling of piston engine working cycle* (in Polish). State Scientific Publishing House (PWN). Warszawa, 1990
10. J. Galindo, J. M. Lujan, J. R. Serrano, V. Dolz, S. Guilain: *Description of a heat transfer model suitable to calculate transient processes of turbocharged diesel engines with one-dimensional gas-dynamic codes*. Applied Thermal Engineering. Vol. 26. Elsevier, 2006
11. Z. Nagórski: *Thermal conduction modelling with the use of spreadsheet* (in Polish). Publishing House of Warsaw University of Technology. Warszawa, 2001
12. R. Viskanta: *Overview of convection and radiation in high temperature gas flows*. International Journal of Engineering Science, Vol. 36. Elsevier, 1998
13. Kowalski J. Tarełko W: *Modelling aspects of nitric oxides emission from the two-stroke ship engine*. Explo-Diesel & Gas Turbine Conference 2003. Międzyzdroje-Lund, 2003
14. Kowalski J: *Alternative method of nitric oxide emission estimation from two stroke ship engines*. Journal of KONES Conference. Vol. 11, No. 1-2. Warszawa, 2004

CONTACT WITH THE AUTHORS

Jerzy Kowalski, M. Sc. Eng.
Wiesław Tarełko, Assoc. Prof. Eng.
Faculty of Marine Engineering
Gdynia Maritime University
Morska 81-87
81-225 Gdynia, POLAND
e-mail : jerzy95@am.gdynia.pl

Main building of Gdynia Maritime University. Photo: Cezary Spigarski