FIELD OF PRESSURE IN ZONE CONTACT ELEMENTS ASSEMBLY PRC STATIONARY QUANTIFICATION

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Abstract

One of the most common worldwide rubbing couple which performs plane-turning motion is a pair of selling rings - cylinder sleeve of a Piston – Ring- Cylinder (PRC) system of a combustion engine. It explains the necessity of performing investigations concerning the phenomenon occurring in rubbing couple PRC. One of the most important issues is the friction losses as well as losses of the working medium from the combustion chamber. Mathematical models of gas flow in the PRC are described in the literature differ in the way of description and scope of the phenomena taken into account. In this paper approach to determine the flow spaces between the rings considering the effect of the geometry of the PRC system has been proposed. Investigation conducted with aid of CFD (Computational Fluid Dynamics) were aimed on determination of flow resistance within the surface between the piston, rings, and cylinder liner. Aim of the study was achieved - The pressure field. it has been found that it is possible to determine the pressure field in the space of the PRC system basing on the approximation of the generalized transport equations for a discrete geometric model using the finite volume method. The precision of the results depends on the account in the form of boundary conditions as well as external conditions.

Keywords: *piston combustion engines, PRC systems, CFD*

1. Introduction

One of the most common worldwide rubbing couple which performs plane-turning motion is a pair of selling rings - cylinder sleeve of a Piston – Ring- Cylinder (PRC) system of a combustion engine. Such PRC system generates significant motion resistance. Different researchers estimate the friction shear of piston rings – cylinder sleeves for 19-60% of overall frictional losses of a combustion engine. The problem of friction loses was assess by such researchers like Akallin et al. [1], Halsband [6], Krzymień [16], Szkurłat [31], Tandara [32] and Tateishi [33]. Despite significant range of the estimations it is easy to find that about 2.5% of mechanical losses are caused by friction of piston rings with sliding surface of a cylinder sleeve. Mentioned argumentation explains the necessity of performing investigations concerning the phenomenon occurring in rubbing couple PRC. One of the most important issues is the friction losses as well as losses of the working medium from the combustion chamber.

Stresses occurring in the PRC systems are consequence of a pressures caused by the combustion process and own elasticity of piston rings systems. The amount of the stress is determined with aid of direct measurements or computations performed by means of numerical models of working medium flow within the PRC system. The direct measurements of the stresses between piston rings were performed and published by Todsen [35] and English [4]. What they found was over tenfold decrease of pressure on first piston ring during the combustion process, hence in the range of 0-20^{o} CA.

The key issue in modelling the flow of the medium is to define the space between the rings of a PRC system and gas flow in those spaces. These pressures are calculated in steps of gas flow through a package of rings, where the boundary values are pressure, measured in the combustion chamber and crankcase. Furthermore, gas flow through the lock ring and side surfaces, upper and lower ring should be taken into account (Fig. 1.)

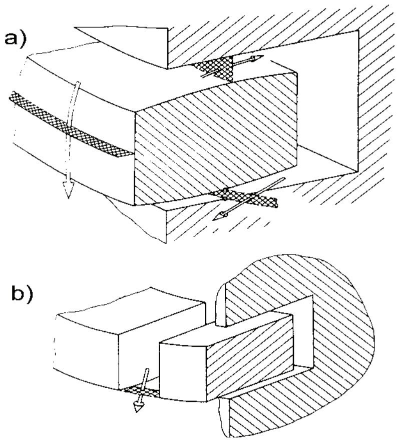

Fig. 1. Exhaust parts on piston ring [14]: on sealing surfaces b) on piston ring joint

In most models it is assume that the flow between the rings, piston and sleeve coats occurs under isothermal transformation. In practice, it is only partially truth because of the very close contact of these elements and their small cross-sections. In this case the knowledge of the temperature of individual elements is indispensable.

Frequently, as a model for the piston ring sealing in the cylinder liner, shall be maze limited by the surface of the sleeve, the side surface of the piston, top, bottom and back of the ring grooves in the piston and piston rings. This is a series of spaces interconnected with throttle slits. The nature of pressure change in the workspace of an engine indicates that the flow in these spaces is transient and its intensity depends not only on cross-leakage, but also on the volume of each space [21].

As shown in Fig. 1. by adjusting the ring in this particular position the flow of gas can take place not only through the lock, but also around the ring. The value of cross-sectional area at the side surface may be tens of times greater than the value of cross-sectional area of the lock [30]. This situation may occur during the radial displacements of the piston ring within the groove.

As a result of the manufacturing process and implemented executive accuracy, the shape of the PRC elements deviates from perfection. This may affect the increase in the intensity of flow through the resulting leaks. Such deviation may be consequence of noncircular cylinder liners, the lack of flatness of the ring grooves shelves, the lack of circularity of the rings after assembly of PRC system, etc. Furthermore, during the operation flow change appears due to wear of the PRC elements. They manifest themselves, for example, by increased wear of cylinder liner in TDC of the first ring.

The value of flow rate is also affected by changing engine operating conditions resulting in temperature changes the geometry of the PRC components of the assembly. The piston in one cycle repeatedly changes its position in the sleeve adjacent to the surface of one or the other part and assuming the position of oblique. This has the effect of changes in cross-sectional area of the lock.

In the spaces between the rings and piston grooves shelves and the surface of the sleeve is lubricating oil, which reduces their volume and ensures caulking. The amount of oil contained on these surfaces depends on surface microgeometry and their wettability with oil.

Mathematical models of gas flow in the PRC are described in the literature differ in the way of description and scope of the phenomena taken into account [21]. The Ting models [34], Furuhama [5] and Mundo [19] assumes that the temperature of the individual steps and their volume are constant and unchanging over time and that flow between stages is done only through the locks of the rings, assuming that their cross-sections are constant. The flow itself is modelled as isentropic flow through the orifice and adjusted by means of the flow coefficient. Furthermore, it is also included that the flow before and after the gap can be subcritical or critical depending on the pressure ratio. What was modelled was three- ring team, laden with forces: the pressure of gases, friction, oil resistance of subsidence on the shelf when the piston groove and the adhesion of the sealing ring. The sealing operation of the wiper ring was omitted. The model by Miyachiki et al. [18] in addition to the listed features includes sealing ring wiper operation, limiting the load to the force derived from gas pressure and inertia. The model by Yoshida et al. [38-40] introduces an additional correlation between the model of sealing and the model of the ring dynamics. This involves taking into account the additional surface area of flow when the ring is not in contact with the ring groove. Similarly, Petris et al. [22] also takes into account the flow around the ring. Although relying on the previously mentioned models, the computation of the cross - section area of a flow was performed differently. Namely it is express, as a weighted sum of the cross-sectional area of the lock and cross-sectional area between the ring and groove. The weights are given in the work of Namazie and Heywood [20] flow coefficients in the lock and the ring groove. Bearing in mind that the field between the surface of the ring and the groove is small and the inaccuracy of the performance, they take into account this value even when the ring rests on the piston groove. Mentioned model of Namazie and Heywood [20] fully recognizes the issue of flow through the lock as well as around the ring. In this case it is assumed that the maze consists of three spaces: two behind the sealing rings and one between them. Like in case of the above-mentioned models the scraper ring sealing action is omitted. The isothermal flow between steps, where the temperature factor is constant and equal to the assumed temperature of the cylinder is considered. The most important novelty is that the spaces for the rings are connected by cross fissures resulting from the instantaneous positions of rings in the grooves. Just as in the models and Furuhama Ting, the flow through the lock is considered as an isentropic flow through orifice including critical and subcritical conditions. Heywood in [8] returned to the model published in conjunction with Namazani, presenting its improved version. Here scraper ring sealing action is considered as well as a static and dynamic lateral twisting of the rings. Axial displacement and dynamic twists are determined as a result of the balance of forces and moments coming from the gas pressure, inertia, resistance of the oil during ring falling onto the piston grooves shelf, the surface pressure between the shelves and ring groove, friction and pressure in a film of oil. The flow through the slot ring - groove is modelled as in [21] and adopted as the isotherm.

Slightly different way of describing the medium exchange between the ring spaces was proposed by Sygniewicz [29]. He changed the assumption of constant temperature, in stages, equal to the cylinder temperature at variable temperature changes resulting from the energy equation inside the medium. In this model, however, it is assumed that the volume stages are constant, and isentropic flow occurs only through locks rings. Cross-sectional area of the lock is changed according to a logarithmic scale, which is related to the initial logarithmic change of the cylinder liner wall temperature along its generatrix. Description of changes of parameters characterizing the system was based on energy and mass balance. This allowed the development of expressions describing the temperature and pressure change in different stages, that is, spaces in between the rings. Sygniewicz model, in addition to all possible cases of movement between steps resulting from the differential pressure and flow subcritical and critical, also takes into account the impact factor of heat exchange between gas and surrounding walls. Furthermore, the model includes the dependence given by: Woschni for turbulent flow, Wiegand for turbulent flow led through the annular cross-section respectively on the outer and inner surface, Michiejew for the flow through the ducts with arbitrarily complex shapes and Pohlhausen for laminar flow, including the boundary layer. Sygniewicz after experimental verification found that the optimal model of heat transfer is described by the equation proposed by Pohlhausen. This is due to the nature of flow that is turbulent only in the space between the rings and only in a very narrow range of rotation of the crankshaft. The Sygniewicz model also takes into account the fact that the gap on the ring locks decreases with respect to movement of the piston from the internal turn towards external turn. Experimental Verification of the model showed only 15% deviation from the values of measured pressures and flows, allowing for a particular engine to determine the volume of blowthrough of exhaust gases to the crankcase, and the pressure between the rings depending on the value of play in the lock, or the volume of space between the rings. Continuation of Sygniewicz research is the development of mathematical models carried out by Smoczyński and presented in [24-28]. Using the pressures calculated by means of Sygniewicz model, Smoczyński computes the forces acting on the piston ring and cylinder axis along the radial direction, so it is possible to determine the axial displacement of the ring in the piston ring groove, the pressure forces the piston ring on the shelf as well as load the oil film between ring and cylinder liner [27]. In later investigations the model is extended with torsional displacement of the ring within the piston ring groove, the ring deformation and the piston-end, which allows determining the angular position of the sliding surface relative to the sealing surface of the piston ring cylinder liner [24, 25]. Finally work [26] enriches it with thermal deformation of the piston, piston ring and cylinder liner. Along with the works discussed in the previous, model calculations used to mechanical deformation of the piston and piston ring allows calculating the angle of inclination of the piston ring seal. This is a starting point for the optimization of the ring sliding surface to reduce friction losses to a minimum.

Model summarizing the previous descriptions of the process of flow in the maze of the PRC system was proposed by Niewczas and Koszalka described in [15, 21]. This model takes into account the impact of PRC wear during the operation of the internal combustion engine, which is manifested by the increase of the play as well as the change of piston rings elasticity. Pressure in the spaces between the rings is integrated with the rings displacements within the grooves. This means that the volume of cross-sectional area of the ring locks are functions of the angle of rotation of the crankshaft, while the cross field of the gap between the rings and ring grooves, arises due to the instantaneous positions of the rings within grooves. The spaces between the rings and behind the rings are examined independently. Therefore the flow between the side surfaces of the rings and grooves and the accumulative effect of space behind the rings is considered. This indicates taking into account flows between the side surfaces of the rings and grooves and the accumulative effect of space behind the rings. The model does not take account of movement between the side surface of the ring and cylinder liner assuming perfect adhesion and the circularity and ring around the circumference of the cylinder liner. The model includes sealing properties of the wiper seal, and thermal deformation of the PRC elements. Moreover, the heat exchange between the gas flowing through the seal and the walls of the maze as considered as well. The working medium flowing through a maze is a semi - perfect gas whose internal energy and specific heat for constant volume and constant pressure are dependent only on temperature. It was assumed that the flow of medium through the gaps is isentropic. The heat between the gases surrounded by walls is exchanged in the steps of the maze. Based on calculations using this model it is possible to obtain not only the pressure in the spaces between the rings, but also the temperature of the PRC assembly components. A particular advantage of this model is possibility of demonstrating the impact of the forecast element wear on the pressure in the spaces between the rings and blowthrough of the exhaust gases into the crankcase. The cited work shows that the scientists engaged in research and mathematical modelling of flow in the ring maze believe that pressures in different areas between the rings are directly related with the force of friction in the PRC. This in turn is a consequence, inter alia, of the materials from which the components are made of, especially the lateral surfaces of the piston ring sealing and cylinder liner.

2. Theoretical basis of CFD.

The general equations that describe any fluid flow are: the continuity equation:

$$\frac{\partial \rho}{\partial t} + div(\rho \upsilon) = 0 , \tag{1}$$

Navier-Stokes equation (the principle of conservation of momentum):

$$\frac{d\upsilon}{dt} = F + \frac{1}{\rho} div P + \upsilon \nabla \vec{\upsilon}, \tag{2}$$

energy conservation equation:

$$\rho \frac{d}{dt}\left(\frac{\upsilon^2}{2} + C_V T\right) = \rho F \upsilon + div(P\upsilon) + div(\lambda grad T) + \rho q(t). \tag{3}$$

Solving these equations gives a complete picture of the flow, however the results can be obtained for very simple laminar flows. In technology mainly turbulent flow is considered, and as such is examined by means of numerical methods. The turbulent flow is observed in pumps, turbines, fans, pouring nozzle, in the wake of bodies, boundary layers, closed ducts.

3. CFD simulation

A substantive schedule of major steps during development of the numerical model is listed below:

- identification of the geometric dimensions,
- translation of the geometry on numerical one,
- discretization of the computing space
- the implementation of boundary and initial conditions
- the selection of computational scheme,
- the selection of turbulence model.

The work was begun with the identification of geometrical dimensions to the nearest hundredth of a millimetre. The next step was the introduction of geometric dimensions for the numerical model, performed with aid of Gambit interface, which is a pre-processor of commercial computing system Fluent.

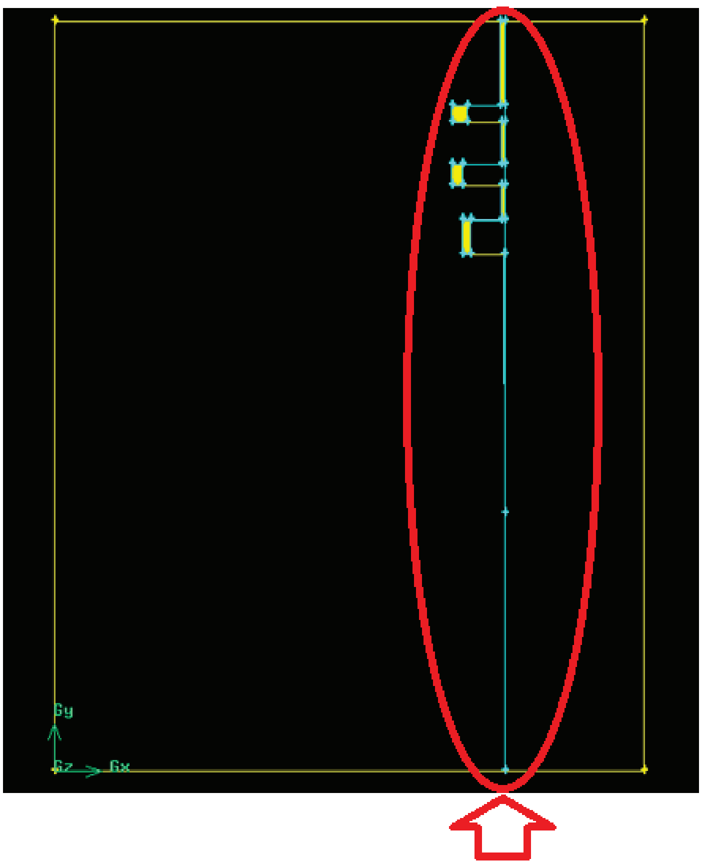

Fig. 2 View of the models geometry

Geometric area of the numerical model (emphasized in Fig. 2) includes the space limited by the surface of the piston ring and cylinder liner.

The third step in the development of numerical model was the discretization of geometrical space.

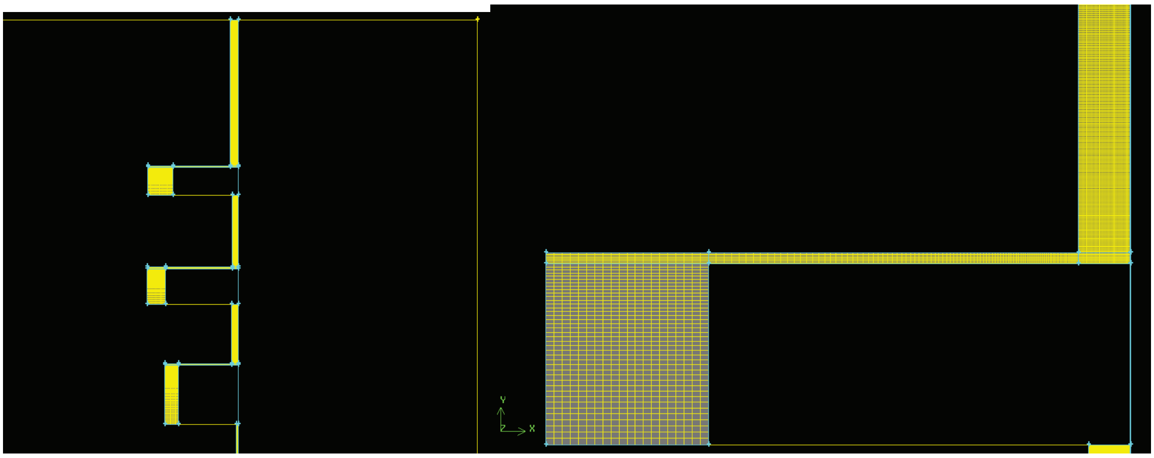

Fig. 3. Discrete form of a geometric model

The discretization was performed using “Quad” type tetrahedral elements due to their better quality comparing with the “Tri” type elements. Tetrahedral elements depicted in Fig. 3 does not exhibit degradation of the diagonals but only minor changes of the sides which was recognized as and acceptable deviation from the ideal squared shape of “Quand” type element.

The fifth step in the construction of numerical model was the introduction of boundary and initial conditions. As a boundary condition was chosen: “pressure inlet” and “pressure outlet” allowing entering the value of pressure in the combustion chamber and the pressure in the crank chamber. The value of mentioned pressures was 5.5 MPa as a condition of the inlet, and 0.2 MPa as a condition for the outlet (terminology typical of computational systems for determining the flow parameters). The boundary condition of a pressure at the inlet was established as an initial condition.

The sixth step in the construction of numerical model was the choice of computational scheme - implicit because of the absolute stability of the model, the adjustment of the step size with respect to speed of the physical phenomena course.

“Reynolds Stress” of fifth order was selected as a turbulence model which supplements the principles of conservation of mass, energy and momentum with a dimensionless coefficients enabling simulation of turbulent flow. Here it is entitled for forced flow in which fluid stream changes their direction as a consequence of change of the cross sectional field.

The culmination of the work devoted to the construction of numerical model was engagement of the computations. Factors such as the large number of elements (approximately $1*10^{6}$) in the discretized 2D computational space requires enormous computing power. Model of turbulence (the most labour-intensive computationally in used software version) triggered the need for labour intensive computing in the iteration equations in a numerical space. The calculation of a single model lasted about 30 hours of continuous computing of the unit operating in accordance with the purchased license for a single thread of the processor.

Aim of the study was achieved. The pressure field is depicted in Fig 4. The maximum pressure occurs at the height of the piston crown and is about 5.5 MPa. This value is maintained up to the first ring. As the flow went around the ring the pressure dropped to about 4.0 MPa. Pressure of 4.0 MPa is maintained up to the second ring. After this ring value of pressure is reduced to about 2.3 MPa. During the flow around a third wiper seal the reduction in pressure to about 1.3 MPa occurs. The value of 1.3 MPa decreases along the length of the piston skirt to the value of 0.2 MPa which prevails in the crank chamber.

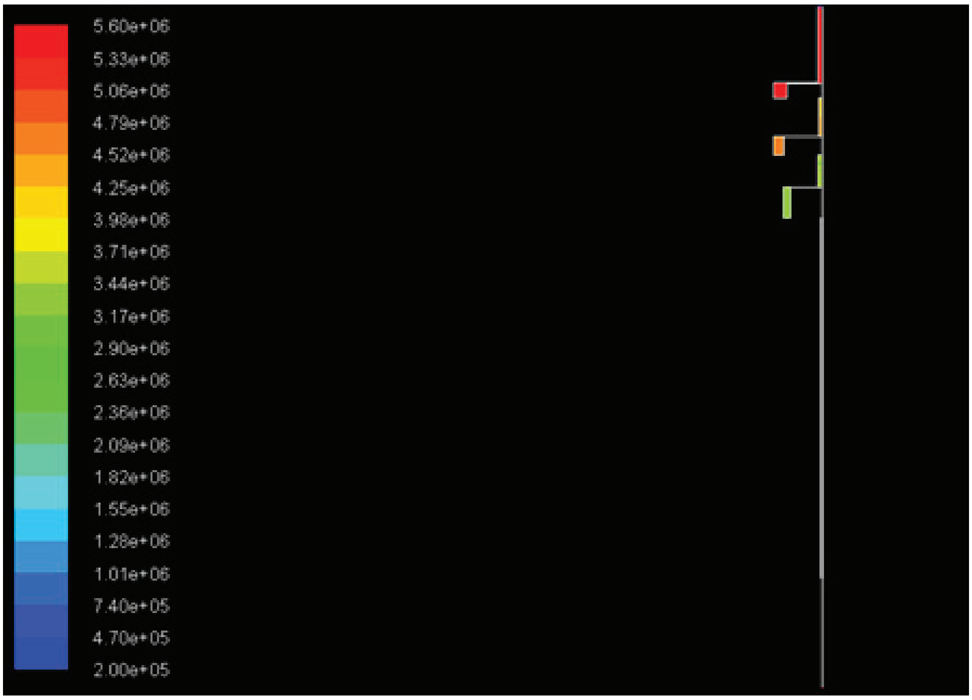

Fig. 4. Pressure field contour

4. Conclusion

It is possible to determine the pressure field in the space of the TPC system basing on the approximation of the generalized transport equations for a discrete geometric model using the finite volume method. The precision of the results depends on the account in the form of boundary conditions as well as external conditions.

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