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Numerical multiphase simulation and validation of the flow in the piston ring pack of an internal combustion engine

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ABSTRACT

The piston ring pack is important for the sealing of the combustion chamber of an internal combustion engine. It plays a major role in friction, wear and oil consumption considerations. Both experimental and theoretical studies in this area are difficult due to the complexity of this highly dynamic system. The paper deals with the numerical investigation by means of computational fluid dynamics of the gas and oil flow in the piston ring pack. Having been validated with experimental data, the simulation results show gas and oil transport mechanisms, which can be used to improve existing models of 0D/1D-simulations. This leads to a better understanding of the processes in the piston ring pack and helps to further optimize the tribological system.

1. Introduction

The piston ring pack is still part of comprehensive research. Reduction of friction, blow-by losses, oil consumption, and wear are the key challenges of the piston assembly development. In order to achieve the optimum of all these targets, it is important to gain an understanding of the oil distribution and the oil transport processes in the ring pack. Numerical simulation of the ring pack flow can be a means to obtain further knowledge of the mechanisms involved. Using 0D/1D-simulations to calculate the piston ring pack, which are based on chamber-orifice models, is state of the art. These models have been under continuous investigation for the last decades and have been gradually improved by implementing increasing model depth. The majority of the 0D/1D-studies focus on the blow-by flow [3,7,10,23], ring/piston dynamics [10,19,20,23], friction and hydrodynamics [2,10,13,19,20] and oil transport/consumption [2,3,7,10,19,22,23] as well as corresponding experimental approaches [1,5,6,11,14,22,24]. However, it is difficult to obtain reliable discharge coefficients for the flow through the piston ring gaps or the flow between the rings and the related grooves. In addition, the oil flow is usually modeled with the Reynolds equation for thin films, which is generally not a good assumption for all parts of the computational domain (e.g. ring grooves). The CFD-simulation of the piston ring pack is able to give new insights and its results can help improving existing 0D/1D-models.

Hronza et al. [8] introduced an improved approach using the 2D-Navier–Stokes equations instead of the Reynolds equation to model the oil phase. This approach considers partially flooded areas and free surface determination of the oil film. However, the interaction between gas and oil phase is only accounted for in the form of a boundary condition. This, in turn, is not sufficient to calculate all occurring oil transport mechanisms in the piston ring pack.

There have only been a few studies about CFD-simulation of the piston ring pack in the past. The authors of [25] introduced a 3D-model of the piston ring pack which considers oil and gas flow. A weakness of this simulation is the neglection of the ring movement, which is a key aspect of all transport processes in the piston ring pack. The authors of the aforementioned paper concluded that the circumferential positions of the ring end gaps only have an insignificant influence on the blow-by.

Other studies deal with cavitation effects on the running surface of the compression ring, which have been validated with experimental data [16,17]. The computational domain of the models is limited to the area around the compression ring, but it shows that even very local effects are investigated in the ring pack.

Latest studies presented a method to calculate the gas flow through the piston ring pack in a diesel engine with a two-dimensional CFD-approach [12]. This method was applied to the ring pack of a gasoline engine and is further enhanced in the present work. Measured pressure and ring movement data allowed the validation of the simulation. The consideration of oil in the simulation allowed to capture a number of oil transport mechanisms in the results. The piston and ring pack of the examined engine is shown in Fig. 1.

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Nomenclature

a	acceleration
c_m	mean piston speed
$\boldsymbol{f}, \boldsymbol{f_k}$	body force field (of phase k)
h, h_k	enthalpy (of phase k)
$\boldsymbol{M_{kl}}$	interfacial momentum transfer term
n	engine speed
p	pressure
p_{cc}	combustion chamber pressure
p_{12}	first ring land pressure
p_{23}	second ring land pressure
$\boldsymbol{q}$, $\boldsymbol{q_k}$	heat flux (of phase k)
t	time
T	temperature
$\boldsymbol{u}$, $\boldsymbol{u_k}$	velocity field (of phase k)
v	velocity
w	volume based heat source
α_k	volume fraction of phase k
Γ_{kl}	interfacial mass transfer term
Λ_{kl}	interfacial thermal energy transfer term
λ	conrod ratio
ρ, ρ_k	density (of phase k)
$\boldsymbol{\tau}$, $\boldsymbol{\tau_k}$	viscous stress tensor (of phase k)
$\boldsymbol{\tau}_k^t$	turbulent stress tensor
φ	crank angle
ATS	anti-thrust side
BB	blow-by
BDC	bottom dead center
CAD	computer aided design
CFD	computational fluid dynamics
ITDC	ignition top dead center
IMEP	indicated mean effective pressure
TDC	top dead center
TS	thrust side

2. Theoretical basics

To calculate the multiphase flow in the ring pack, the following basic equations of numerical fluid mechanics are essential: mass, momentum and energy conservation. The mass conservation law defines the time dependent changes in mass to be equal with all mass flow changes in a control volume [4].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

The momentum conservation is a vector equation. For all spatial directions, the time dependent change in momentum is equal to all applying forces on the control volume. The forces can either be surface or volume forces [4].

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}^{\boldsymbol{T}}) = \nabla \cdot \boldsymbol{\tau} - \nabla p + \rho \boldsymbol{f} \tag{2}$$

In addition, consider temperature gradients in the piston ring flow, the energy conservation equation was solved. The time dependent change of energy is equal to the work performed on the control volume [4].

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} h) = \nabla \cdot (\boldsymbol{\tau} \boldsymbol{u}) - \nabla \cdot (p \boldsymbol{u}) + + \rho \boldsymbol{f} \cdot \boldsymbol{u} - \nabla \cdot \boldsymbol{q} + \rho w \tag{3}$$

Both oil and gas phase in the piston ring pack flow coexist with a significant volume fraction. For that reason, a multi-fluid approach was chosen to model the flow. With this approach, the entire set of conservation equations was solved for each single phase. Accordingly, the volume fractions of all phases must sum up to 1.

$$\sum_{k=1}^{N} \alpha_k = 1 \tag{4}$$

The simple mass conservation equation is extended with the volume fraction α and a term to consider mass exchange between the phases. Flow phenomena such as evaporation or cavitation can be taken into account with this term. For the calculation of the piston ring pack flow, no mass exchange was modeled between the gas and the oil phase. The general mass conservation equation for multiphase flows can be stated as (cf. [9])

$$\frac{\partial (\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u_k}) = \sum_{l=1, l \neq k}^{N} \Gamma_{kl} \tag{5}$$

The momentum conservation equation is also extended with the volume fraction α for multiphase calculations. Momentum exchange between the phases has been considered for the calculation of the ring pack. The exchange model takes into account the relative velocity of the phases and drag coefficients dependent on the Reynolds number. This approach allows for the modeling of the momentum exchange and captures the interaction of the different velocity fields. A general formulation of the multiphase momentum conservation equation is shown in Eq. (6) [9].

$$\frac{\partial (\alpha_k \rho_k \boldsymbol{u_k})}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u_k} \boldsymbol{u_k^T}) = \nabla \cdot (\alpha_k \boldsymbol{\tau_k}) - \nabla (\alpha_k p_k) + \alpha_k \rho_k \boldsymbol{f_k} + \sum_{l=1, l \neq k}^{N} \mathbf{M_{kl}} \tag{6}$$

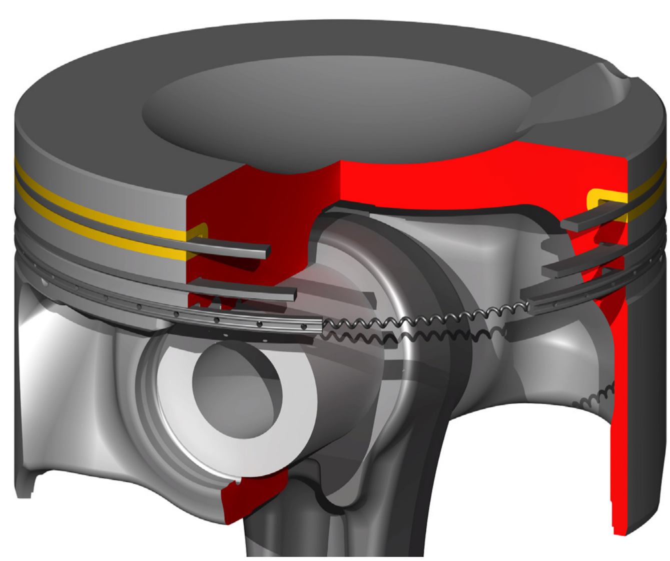

Fig. 1. Piston and ring pack of the examined engine.