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Numerical Simulation of Labyrinth Oil and Gas Separator in Vehicle Engine

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ABSTRACT:
The working process of oil and gas separator is a very complex gas-liquid two-phase separation movement; it is difficult to obtain internal flow condition using analytical method. In this paper, with DPM, SIMPLE algorithm and random walk model, velocity distribution, pressure distribution, oil droplets motion trajectory and separation efficiency were analyzed by numerical simulation method. This analysis is helpful to understand flow law of gas-liquid two-phase fluid in oil and gas separator， and then optimize separator structure, short its development cycle, which has important application value in engineering.

KEYWORDS:
Vehicle; Oil and gas separator; Numerical simulation; Two-phase flow model; DPM

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1. Introduction

In working process of vehicle engine, combustible mixture gas and burned gas in the combustion chamber enter into the crankcase, and form crankcase "blow-by", which is complex mixture comprised of air, burned gas, oil droplets, water vapour and particulate. If the blow-by in the crankcase is not discharged, it can dilute oil, break down performance, so, oil can flow away. At the same time, oil losing into the atmosphere will increase pollution to atmosphere. Now, crankcase ventilation system is widely used in vehicle, it can sent blow-by back to the air intake system and mix with fresh gas, then the blow-by was burnt in the combustion chamber in order to reduce pollutants emissions [1]. Oil and gas separator is one of the most important parts in crankcase ventilation system, after that the blow-by was separated in oil and gas separator, oil droplets enters into the oil sump, the blow-by is sent back to combustion chamber for combustion, which cannot only reduce emissions of harmful substances, but also reduce oil consumption [2].

The working process of oil and gas separator is a very complex gas-liquid two-phase separation movement; it is difficult to obtain internal flow condition using analytical method [3]. In this paper, with discrete phase model (DPM), SIMPLE algorithm and random walk model, velocity distribution, pressure distribution, oil droplets trajectory and separation efficiency were analyzed by numerical simulation method. By this analysis, we can understand gas-liquid two-phase flow law in oil and gas separator, so it provides basis for the design and optimization of oil and gas separator.

2. Mathematical model

There are three kinds of basic models in numerical simulation of gas-liquid two-phase fluid: the first is single fluid model, in which, gas-liquid two-phase fluid is regarded as mixture fluid, the second is two-fluid model, in which, gas-liquid two-phase fluid is regarded as two fluids that mutually independent and interaction, the third is DPM, in which, gas or liquid is regard as background fluid, and the other phase is regard as particles dispersed in background fluid. In these three kinds of models, the first two kinds of models, that is, single fluid model and two-fluid model apply Euler-Euler method, so they are called Euler-Euler model. DPM applies Euler-Lagrange method, so it is called Euler-Lagrange model [4].

2.1. DPM

In numerical simulation of gas-liquid two-phase fluid, DPM is the most commonly used, which is used to calculate droplet flow and bubble flow. It is assumed that volume of droplets or bubbles (collectively called particles later) cannot be too large, and they uniformly distributed in continuous phase, that is, the local volume concentration of particles is less than 10% in this model. DPM belongs to Euler-Lagrange model. In calculation, gas is regard as continuous phase, droplets is discrete phase distributing in continuous phase. Firstly, flow field velocity and turbulent kinetic energy are obtained through calculation of continuous phase, secondly, the single droplet trajectory is integrated in Lagrange coordinates, and then droplet trajectory is got [5]. Turbulent flow field got from calculation is mean flow field because turbulent calculation takes place under concept of statistical average, so single droplet trajectory calculation is nonsense, and obtaining statistical law of droplet motion by calculating a large number of droplet trajectories have practical significance only.

DPM can simulate a large number of droplets motion by calculating a large number of droplets. In this paper numerical simulation of gas-liquid two-phase flow field is studied, in this study, gas is continuous phase, and oil droplets are discrete phase. Oil droplet is very sparse in mixture gas, its volume fraction less than 10%, moreover, there are definite boundary conditions in inlet and outlet of two-phase flow field, and so, it is appropriate that DPM is applied in numerical simulation of gas-liquid two-phase fluid.

2.2. Motion equations and trajectory equations

Force between gas flow and oil droplet in DPM is [6-7]:

$$F = \sum (F_D + F_Q) * m_S * \Delta t \quad (1)$$

Where, m_S is oil droplet mass, F_D is gas flow resistance, F_Q is the other force, F_Q may includes different force, for example, gravity, buoyancy, pressure, temperature gradient force, Brownian movement force, false mass force, Basset force, Magnus force and Saffman force. In gas-liquid two-phase flow of separator, because diameter of oil droplet is very small, concentration is very dilute, so fluid drag is very important, the other force is very small in magnitude compared with fluid drag, so the other force can be neglected. Expression of FD is:

$$F_D = \frac{18\mu C_D \mathrm{Re}}{24\rho_s d^2}(\mu_s - u) \quad (2)$$

Where, u_s is liquid phase velocity, u is gas phase velocity, C_D is drag coefficient, ρ_s is oil droplet density, is gas phase density, d is oil droplet diameter, Re is the relative Reynolds of oil droplet:

$$\mathrm{Re} = \frac{\rho_c d}{\mu}|u_s - u| \quad (3)$$

The momentum equation of oil droplets per unit mass is:

$$\frac{d\mu_s}{dt} = -(F_D + F_Q) \quad (4)$$

Force of oil droplet and reaction force of gas is reverse, so a minus sign is added in the right of above equation. By integrating the momentum equation, motion trajectory equation of oil droplets can be obtained:

$$x_s = \int u_s dt \quad (5)$$

Separation efficiency is an important index for evaluating the separation performance, it equals captured oil droplet mass relative to oil droplet mass entered the cover per unit time.

$$\eta = \frac{S_2}{S_1} = \frac{S_1 - S_3}{S_1} = 1 - \frac{S_3}{S_1} \quad (6)$$

Where, S1 - mass flow of import oil drops (kg/s), S2 - mass flow of collected oil drops (kg/s) S3 - mass flow of export oil drops (kg/s). In addition, η may also be expressed as the following equation based on actual operation and analysis by model and software:

$$\eta = \frac{N_1 - N_2}{N_1} = 1 - \frac{N_2}{N_1} \quad (7)$$

Where, N_1 is unit number in Entrance; N_2 is unit number with oil outflow in export.

3. Simulation calculation

SIMPLE algorithm is one of the most widely used methods in engineering field, so, in this paper, SIMPLE algorithm is used to calculate gas phase field, DPM is used to track oil droplets trajectory, the stochastic trajectory model is used to simulate the influence of turbulence on oil droplet trajectory, and motion law of oil droplets in oil and gas separator is obtained. The calculation process is shown in Fig. 1

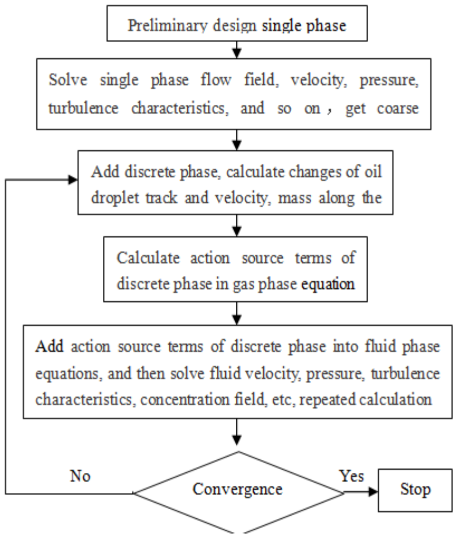

Fig. 1: Calculation process diagram

3.1. Geometric model

The oil and gas separator realizes separation of oil and gas by means of internal centrifuges, cyclones and labyrinth. Taking into account cost and actual separation effect, in recent years, the domestic vehicle companies mainly use labyrinth separator. The labyrinth oil and gas separator is also called the baffle-type oil and gas separator, and its working principle is to block the mixture by installing the labyrinth baffle in the flow direction of the mixture. The main function of the baffle is changing the direction of gas flow, so that the oil droplets collide with the wall under the action of inertia force and remain on the wall, so as to achieve separation purpose of oil and gas [8]. In this paper, a labyrinth oil and gas separator was analyzed using numerical simulation method [9-10], the geometric model of labyrinth oil and gas separator is shown in Fig. 2.

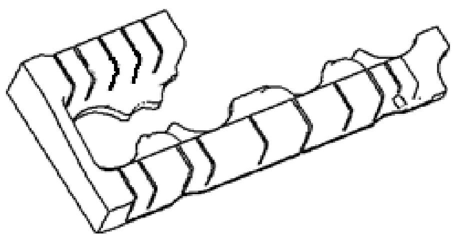

Fig. 2: Geometric model of oil and gas separator

3.2. Parameter setting

Model setting:

- Time model: Steady state model.
- Multi-phase treatment: Lagrangian multi-phase model, two-phase flow includes air and oil droplet.

- Thermal model: Thermal model considering temperature change, heat transfer and thermal radiation
- Turbulence model: High Reynolds number model.
- Medium physical properties: P, T, ρ, μ. etc. of oil and gas.

Algorithm settings:

- Solver algorithm: SIMPLE algorithm.
- Relaxation factor: Relaxation factor of the calculated physical quantities was all selected.
- Difference scheme: Upwind difference scheme.

Material information:

Separator material is PA66 + 15% Mineral + 25% GF, it's elastic modulus is 2084 MPa (150°C, RH0), Poisson's ratio is 0.33, density is 1470 kg/m^3, thermal expansion coefficient is 3.5×10^{-5} m/m/ºC.

Boundary condition:

Calculated fluid is incompressible air, gravity was considered in calculation. Physical properties of oil and gas were shown in Table 1.

Information of mesh and software:

FAME Grid is used. The boundary layer was set two layers, and grid was properly encrypted in high velocity region. Information of mesh is given in Table 2.

Table 1: Physical properties of oil and gas

Property	Fluid properties (Blow-by-gas)	Particle properties (Oil droplets)
Temperature	80°C	80°C
Density	1 kg/m³	800 kg/m³
Pressure	101325 Pa	
Viscosity	2.09x10-5 Pa*s	

Table 2: Information of mesh and software

Mesh type	Tetra mesh
No. of elements	696,000
Mesh size	2mm
Software	STAR-CD 3.2

3.3. Simulation results and analysis

3.3.1. Velocity distribution

Under the working condition that oil droplet diameter is 10 *μm*, gas velocity distributions in oil and gas separator were shown in Figs. 3-6 when inlet velocity is 1m/s, 2m/s, 3m/s, 4m/s. The outlet velocity of oil and gas separator increases with the increase of inlet velocity, and the growth of outlet velocity is more obvious than that of inlet velocity.

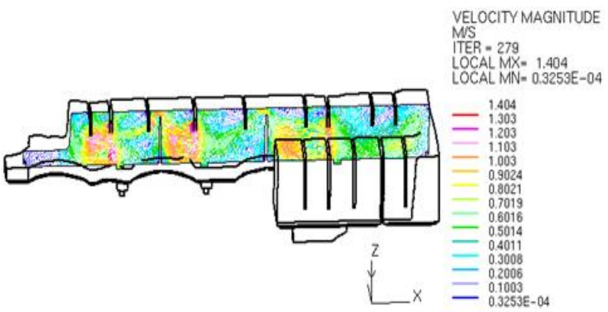

Fig. 3: Velocity distribution of 1m/s inlet velocity

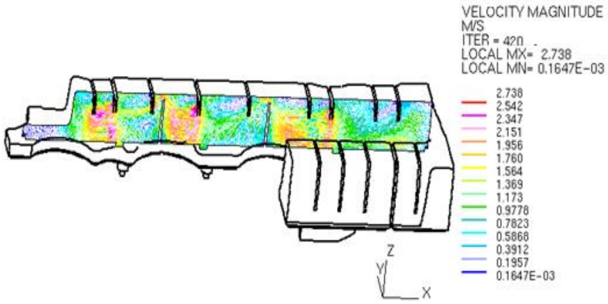

Fig. 4: Velocity distribution of 2m/s inlet velocity

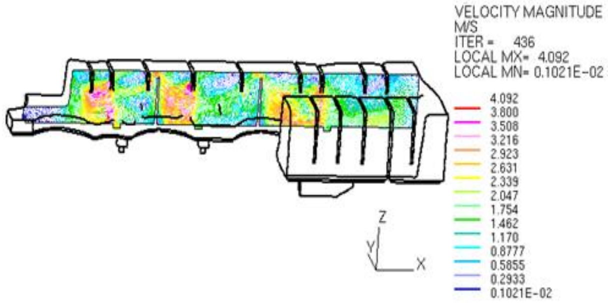

Fig. 5: Velocity distribution of 3m/s inlet velocity

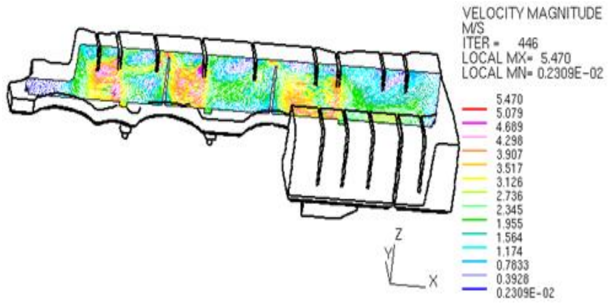

Fig. 6: Velocity distribution of 4m/s inlet velocity

3.3.2. Pressure distribution

Under the working condition that oil droplet diameter is 10 *μm* ,gas pressure distributions in oil and gas separator were shown in Figs. 7-10 when inlet velocity is 1m/s, 2m/s, 3m/s, 4m/s. The pressure distribution in inner wall of oil and gas separator is uniform, but variation of pressure difference is very large at outlet. In oil and gas separator, when gas passes through a series of baffles, pressure changes obviously, and pressure distribution is not uniform near the baffle. With continuous change of inlet velocity, pressure difference and pressure distribution are also different.

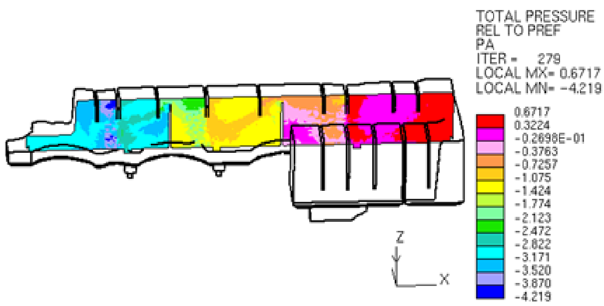

Fig. 7: Pressure distribution of 1m/s inlet velocity

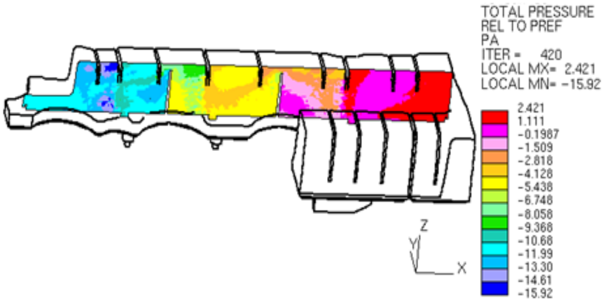

Fig. 8: Pressure distribution of 2m/s inlet velocity

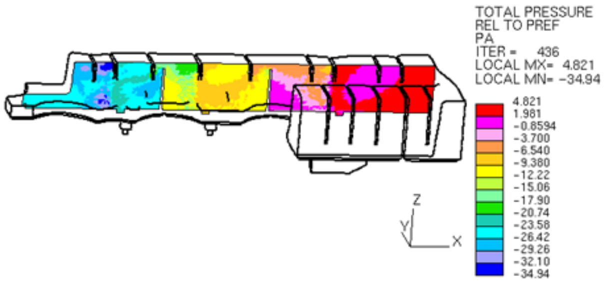

Fig. 9: Pressure distribution of 3m/s inlet velocity

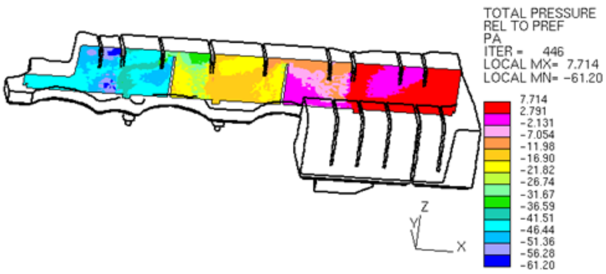

Fig. 10: Pressure distribution of 4m/s inlet velocity

3.3.3. Motion trajectories of oil droplets

Under the working condition that oil droplet diameter is 10 μm, motion trajectories of oil droplets in oil and gas separator were shown in Figs. 11-14 when inlet velocity is 1m/s, 2m/s, 3m/s, 4m/s. When the other factors are constant, oil droplet trajectory is affected by inlet velocity, but the effect is not obvious, when the velocity is small, consistency of oil droplet trajectory is better.

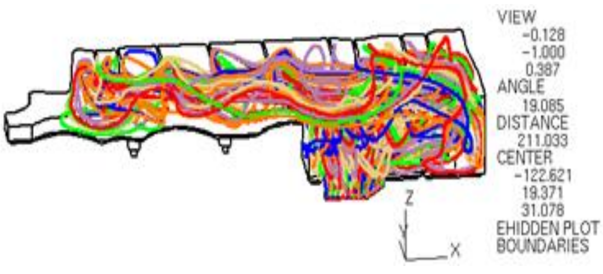

Fig. 11: Oil droplets trajectories of 1m/s inlet velocity

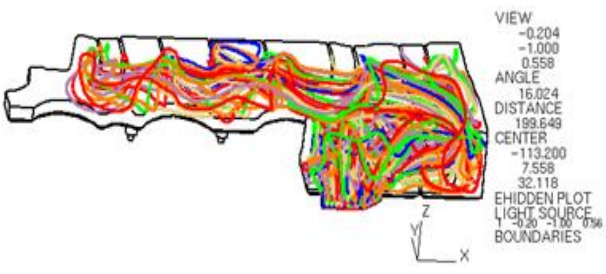

Fig. 12: Oil droplets trajectories of 2m/s inlet velocity

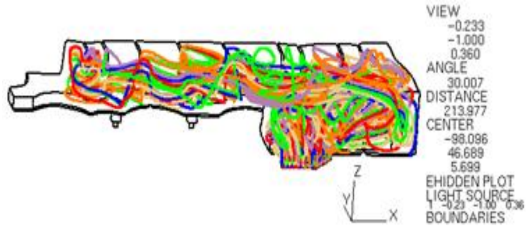

Fig. 13: Oil droplets trajectories of 3m/s inlet velocity

Fig. 14: Oil droplets trajectories of 4m/s inlet velocity

3.3.4. Separation efficiency of oil-gas separator

Separation efficiency of oil and gas separator was shown in Fig. 15 when oil droplet diameter is 10 μm and inlet velocity is 1m/s, 2m/s, 3m/s, 4m/s. Separation efficiency of oil and gas separator was shown in Fig. 16 when oil content is 5g/m^3 10 g/m^3 20 g/m^3 50 g/m^3 80 g/m^3 respectively. At the beginning, separation efficiency increases with the increase of inlet velocity. When velocity increases to a certain value, separation efficiency has a downward trend. When velocity continues to increase, separation efficiency begins to increase again. So it can improve separation efficiency by choosing a suitable speed value. As can be seen from Fig. 16, separation efficiency is affected by inlet concentration, however separation efficiency does not increase with the increase of inlet concentration, but have a concussive change. When inlet concentration is at a certain value (near 20 g/m^3), oil and gas separator has the maximum separation efficiency.

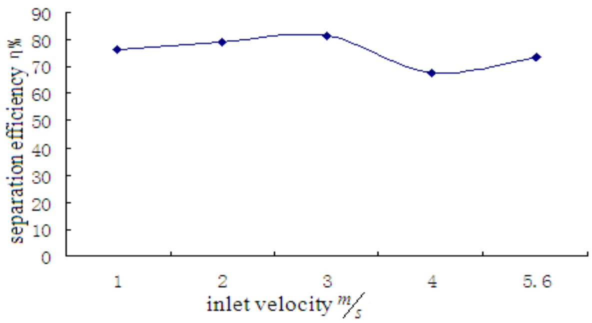

Fig. 15: Separation efficiency under different inlet velocities

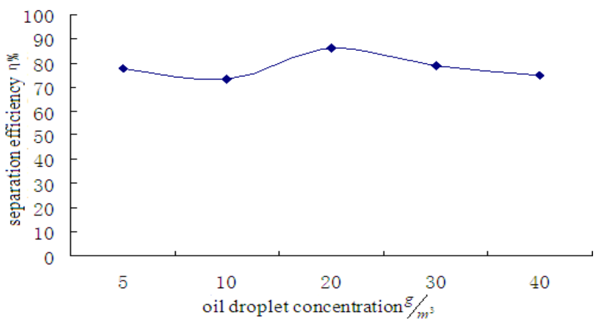

Fig. 16: Separation efficiency under different oil droplet concentration

4. Conclusions

Numerical simulation of gas-liquid two-phase flow motion in labyrinth oil and gas separator was carried out by DFM and SIMPLE algorithm in this paper. On the basis of thorough understanding of labyrinth oil and gas separator model, velocity distribution, pressure distribution, oil droplet motion trajectory and separation efficiency were studied. Although gas velocity, pressure distribution and oil motion trajectory in oil and gas separator are complicated, there are some rules to follow. Gas velocity, pressure distribution and oil droplet motion trajectory have a certain difference when inlet velocity, droplet concentration and droplet diameter are different. Outlet velocity of oil and gas separator increases with the increase of inlet velocity, and the growth of outlet velocity is more obvious than that of inlet velocity. The pressure distribution in inner wall of oil and gas separator is uniform, but variation of pressure difference is very large at outlet. Oil droplet trajectory is affected by inlet velocity, when velocity is small, consistency of oil droplet trajectory is better.

Separation efficiency of oil and gas separator is affected by inlet velocity and droplet concentration. With the increase of inlet velocity, separation efficiency of separator gradually increased firstly, when velocity increases to a certain value, separation efficiency began to decline, when velocity continues to increase, separation efficiency begins to rise again. At the same time, oil concentration in inlet also has influence on separation efficiency, with the increase of oil concentration, separation efficiency decreases firstly and then increases and then decreases, changing in a concussive change, when inlet concentration is at a certain value (near $20g/m^3$), oil and gas separator has the maximum separation efficiency. Therefore, separation efficiency can be improved effectively by selecting appropriate velocity and oil concentration.

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