OIL-AIR-MIXTURE-BEHAVIOUR INSIDE THE COOLING-CHANNEL OF A VW-TDI®-PISTON WITH 2-PHASE-PIV (2-P-PIV)

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Abstract

The pistons used in modern TDI® diesel engines have a cooling gallery near the piston recess for improved piston cooling. That is flooded with engine oil to increase reliability and power potential by reducing component temperature. The flow conditions, in particular the oil mass flow in the gallery, are decisive for the heat transfer from the piston to the oil.

In order to describe the behaviour of the mixture of liquid and gas in real conditions and to determine the oil velocity, complex experiments were carried out using a visible piston in a normal crankcase without a cylinder head. A piston with a transparent head was used to provide a clear view of the two-phase flow from above. The flow processes in the whole ring-shaped gallery are shown using a high-speed video camera and stroboscopic laser illumination.

The density difference at the phase change-over between oil and gas is used as an optical marking to describe the velocity of the fluid.

The picture sequences of the oil-gas mixture are analysed using an algorithm, as used with the Particle Image Velocity (PIV) technique. PIV is achieved on the reflecting structures of the surface of the oil without tracers, this technique is called Boundary-PIV (B-PIV) or 2-Phase-PIV (2-P-PIV). The result is a two-dimensional, time-resolved oil velocity related to varied parameters.

Intention and Basic Observations

The output of diesel engines has increased considerably in recent years. As the increases were achieved with the same crankshaft speeds, this was an immediate result of increased pressure in the combustion chamber. Also the temperatures of many parts increase particularly due to the larger mass of gas.

One of the components affected most by a performance increase is the piston that transfers the work applied by the gas to the crankshaft drive and therefore plays a central role in the engine.

The engine oil is used as the coolant. A good cooling effect is achieved when a ring-shaped gallery with an inlet and outlet is integrated in the piston. The oil is sprayed into the gallery and flows back into the crankcase.

The gallery runs around the recess, near the very hot recess neck. This allows good heat transfer from the piston to the engine oil.

If the piston cooling is to be improved using engine oil, we need to know about the exact flow conditions inside the gallery. To establish which parameters influence cooling, this paper will illustrate the movement of the two-phase flow and provide a statement on the velocity of the oil (and the filling of the gallery).

As the whole gallery needs to be visible, we will look at the piston from above, parallel to the direction of movement. A partly transparent piston has been constructed for this purpose. The head of a standard piston was prepared so that a Plexiglas section could be screwed on top. The gallery is only opened slightly from above and is closed with the transparent part.The volume of the gallery is reduced to a negligible extent. The bottom surface of the Plexiglas is smoothand flat so that the view of gallery is not distorted.

The quality of the oil stream (speed, break-up) leaving the injector (shape, outlet diameter) and the entry into the piston opening influence the flow inside the piston to a great extent. Hence a standard production injector is used in the normal position.

Plexiglas is used as the transparent material and is very sensitive to temperature. The temperature of the oil is therefore set very low and a test oil is used whose viscosity at 20°C corresponds with that of normal engine oil at 120°C.

The following different basic conditions and forces that affect the oil are important for the flow conditions in the channel and thus for heat transfer from the piston to the oil:

- Crankshaft position α
- Flow into the filling pipe
- Contact with piston: Transfer of the momentum from the oil to the piston
- Substantial deflection into the ring gallery
- Acceleration due to piston movement carries the oil up or down (top or bottom of gallery)
- Angled position of gallery at approximately 5° causes movement in horizontal direction
- Centrifugal force caused by curve of gallery carries the oil outward
- Friction of the oil on the rough walls
- Friction in the oil (viscosity)
- Interactive forces of the oil with the gas

Depending on the crankshaft position, the injector reaches deep inside the piston or is a great distance away from it. The crank angle α is therefore particularly important for the flow of oil into the piston as well as the filling of the gallery.

Furthermore the acceleration of the piston, which is quadratically dependent on the crankshaft speed, has a big influence on the movement of the oil in the gallery.

Test Set-up

Figure 1 shows the basic test engine and test equipment. The oil pump transports the oil through a heat exchanger and through a throttle. The temperature and the pressure are measured and set as required. The oil

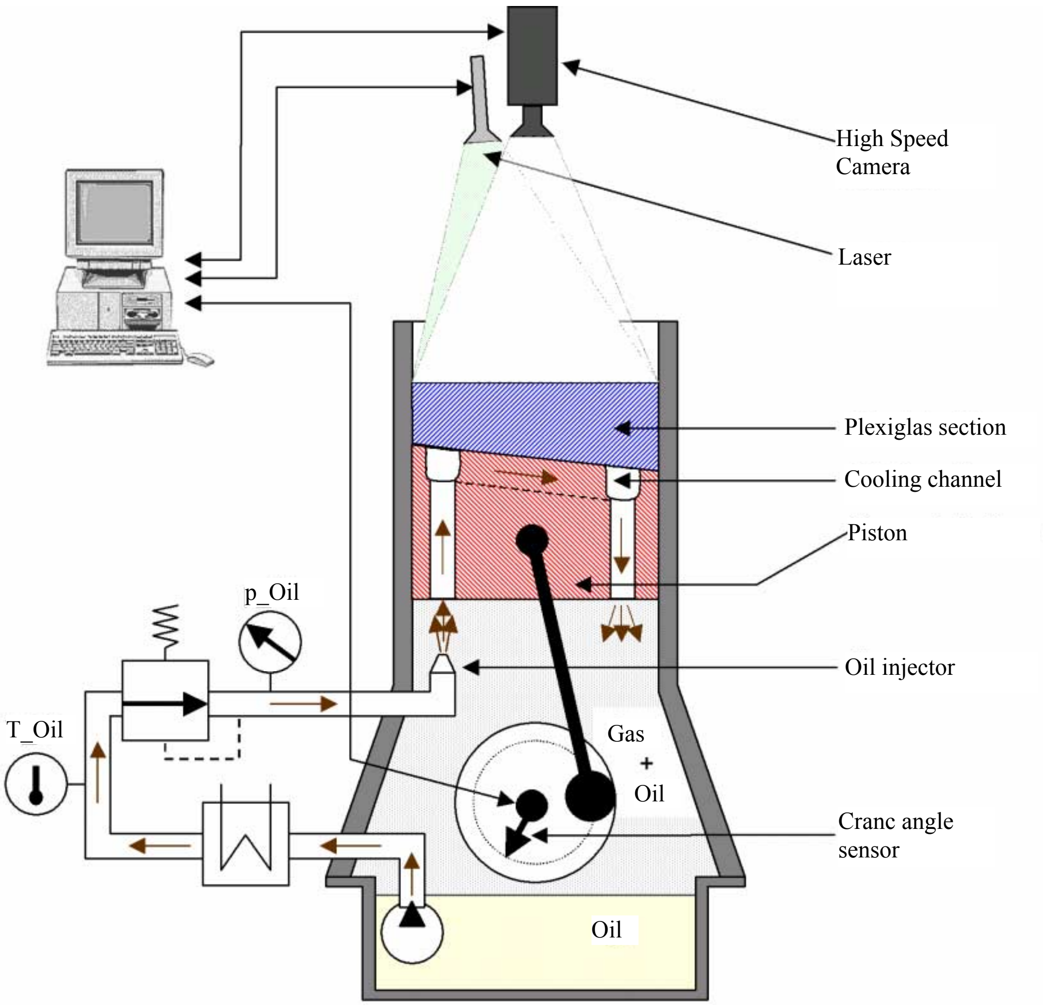
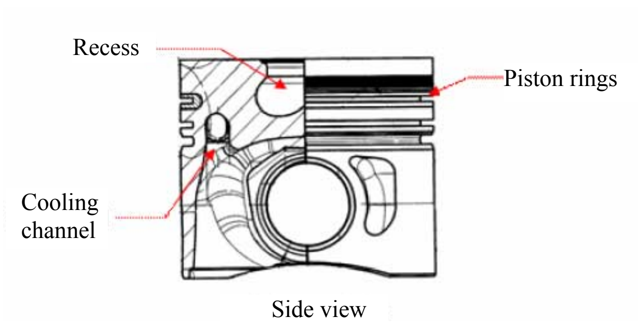


Fig. 1: Diagram of the test engine and the measuring equipment

accelerates to a high velocity inside the injector. Depending on the crankshaft position, it is sprayed underneath the base or into the filling gallery of the piston. The oil flows through the cooling gallery with considerable deflection and leaves the piston back into the crankcase where there is a mixture of gas and oil droplets.
The test piston and the Plexiglas section are shaded.

The position of the cooling gallery in a standard piston can be seen in a cross-section at the top of Fig. 2. The top part of the piston was removed for the measurements and replaced with Plexiglas. The bottom part of Fig. 2 shows the ring-shaped cooling gallery and the position of the inlet and outlet bore holes.



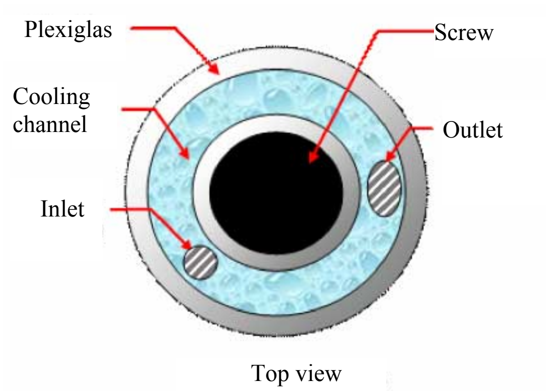


Fig. 2: Transparent piston (side view and bird's eye view)

Measuring Technology

High-speed films
A high-speed video camera was used to visualise the movement of the oil in the cooling gallery of the piston. The video camera runs at a frame rate of up to 12,000 frames per second. An Nd:YLF laser with a pulse duration of approx. 200 ns and a pulse energy of approx. 1.5 mJ at a wavelength of 527 nm (green spectral band) is used to illuminate the processes. The laser emits one light pulse per frame. The light is fed in via an optical fibre as floodlight illumination. The camera resolution is 256 * 256 pixels. The laser and camera are triggered by the motor in relation to the crank angle. This technique allows the scattered light of the liquid and gas mixture to be visualised with a high time resolution over several successive piston cycles. It can then be analysed later on.

Particle Image Velocimetry (PIV)
Quantitative flow measurements are mainly carried out using Particle Image Velocimetry (PIV) [1]. With this measuring technique, the speed of a fluid element is determined indirectly by defining the velocity of a tracer particle that is added to the fluid. In two-phase flows like the oil and air mixture inside the cooling gallery, the density gradient between gas and liquid can be used directly as a tracer. In this case, the velocity of the fluid can be measured without adding tracers. A light sheet is not used.

The PIV algorithm was used directly on image pairs from the high-speed video recordings to determine the oil movement in the cooling gallery. The image pairs are recorded with a time delay of 83 µs. The particles have therefore moved in this time interval according to the flow conditions. The PIV images are evaluated by calculating the 2D cross-correlation [2] of these image pairs. Combined with the high-speed recordings, the result is a two-dimensional vector field of particle movement with high time resolution.

Measurements

The selected measuring set-up allows both monitoring and also illumination of the processes in the piston cooling gallery from above (see Fig. 1). It is therefore possible to record the full piston stroke at one camera angle with high-contrast and evenly illuminated images. The reflections, which cannot be avoided, do cause a problem in the image with this set-up. A typical measurement image is shown in Fig. 3.
The position of the inlet and outlet bores, the width of the cooling gallery and the main flow direction of the oil are indicated in Fig. 2. The oil gallery is filled in bursts over several piston strokes. The pictures show the reflections formed on the density gradients and the surface structure of the fluid particularly well.
Simply watching the high-speed recordings allows you to draw the first conclusions on the processes in the

piston cooling gallery. The gallery was not filled completely with oil at any point during operation. There was always a mixture of oil and air in the gallery. During the downward movement of the piston, the oil was pressed against the Plexiglas and it was difficult to see inside the gallery. However, during upward movement, the acceleration acting on the oil is reversed and pushes the oil against the gallery floor. In this phase, you can clearly see the two phase action with the naked eye as the view of the gallery is not blocked. The flow of oil into the inlet bore and the flow through the gallery can also be seen clearly in the high-speed films.

To obtain quantifiable data on the flow conditions, the films are evaluated with PIV (see above).

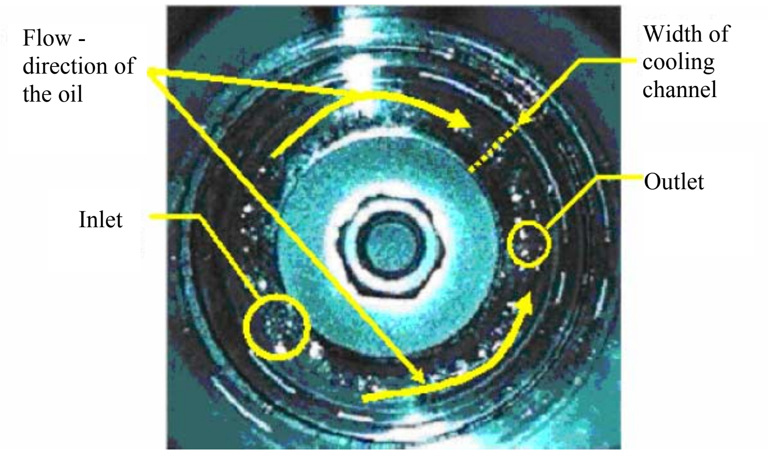


Fig. 3: Typical measurement image

Evaluation

The high-speed film images are evaluated using cross-correlation of subsequent measurement images. This allows the oil velocity in the cooling gallery to be calculated. Three evaluation windows have been defined that represent the flow velocities in the gallery. Window 1 is directly next to the oil inlet bore. This area allows to determine the velocity of the oil as it enters the gallery. Window 2 and 3 are next to the outlet bore and represents the outlet flow. A typical vector field for the gallery flow as well as the position of evaluation windows 1 to 3 is shown in Fig. 4.

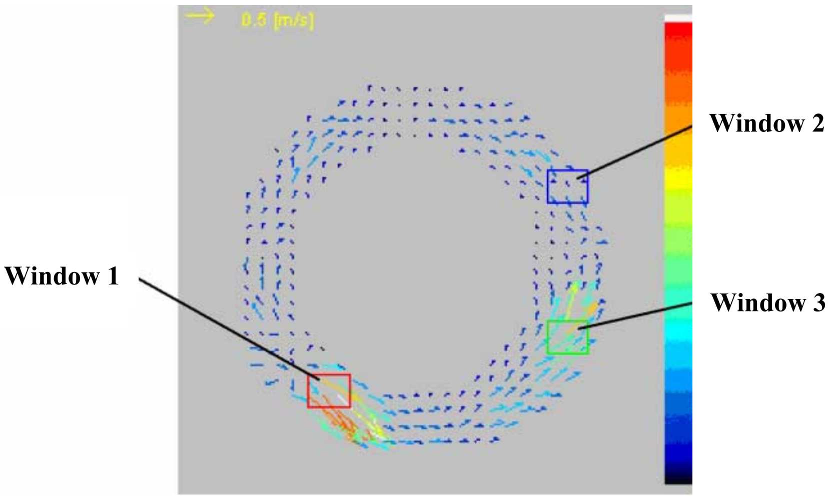


Fig. 4: Evaluation zones in the cooling gallery

It is clear to see that the oil flows into the cooling gallery at high speed, flows evenly at a lower speed in the direction of the outlet bore and then leaves the gallery at a slightly higher speed.

The development of the oil speed in the three evaluation windows is shown in Fig. 5 in relation to the oil injection pressure. The speeds within the evaluation window are averaged. To suppress the influence of cyclical fluctuations, averaging was also carried out over five subsequent piston strokes.

The oil velocity in the area of the inlet bore increases as the oil injection pressure rises (evaluation window 1) while the flow velocity in the gallery and in the outlet zone (windows 2 and 3) is independent. The greater momentum of the oil at a higher injection pressure cannot be converted into a higher flow velocity in the gallery as most of the momentum is transferred from the oil to the piston.

The movement in the oil gallery is recorded with frame rates of up to 12,000 images per second on the high-speed camera. This corresponds with a time resolution of 1°CA per image. This also allows the time development of the flow velocity in the piston oil cooling gallery to be defined with a high time resolution.

The ring gallery is divided into two new evaluation zones, which lie away from the inlet and outlet areas, to represent the flow in the channel, independent to the flow close to the both bores.

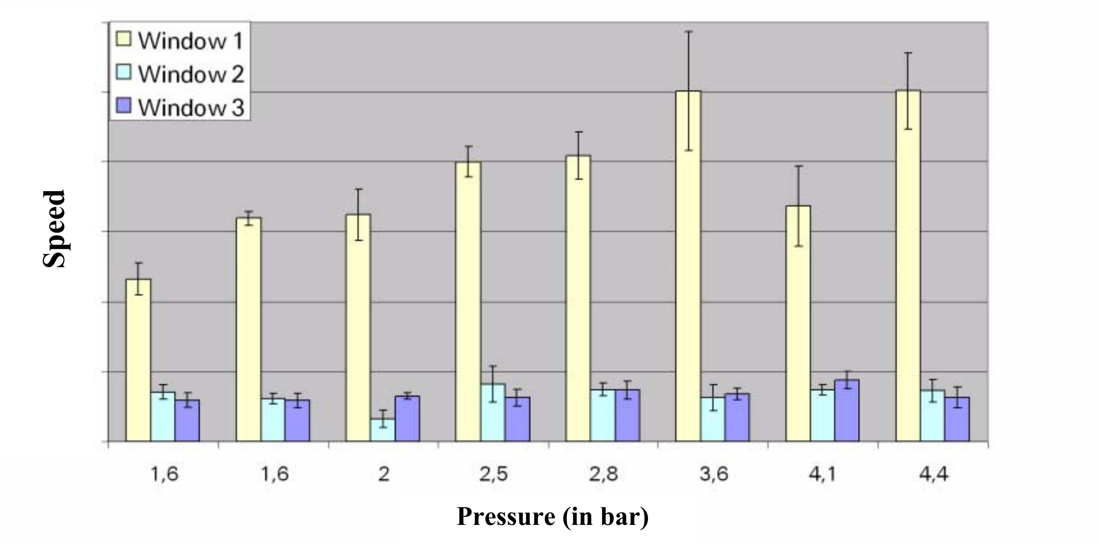


Fig. 5: Average velocity at 2000 rpm in relation to the injection pressure

Fig. 6 shows the tangential velocity components of the oil flow. It seems that the piston acceleration plays the decisive role for the time-resolved tangential velocity of the oil in the cooling gallery.

Between approx. -50°CA and +110°CA after TDC an oscillating, pulsating flow with high velocity gradients is obtained. The velocity of the oil in the cooling gallery seems to be meanly influenced by the acceleration forces of the piston movement. In the remaining time area a lower and comparatively constant tangential oil velocity without change of sign can be recognised. The flow seems to be characterised by the penetration depth of the injection nozzle into the inlet bore.

These results impressively show the complexity of the flow processes in the cooling gallery of a piston and how they can be measured and recorded.

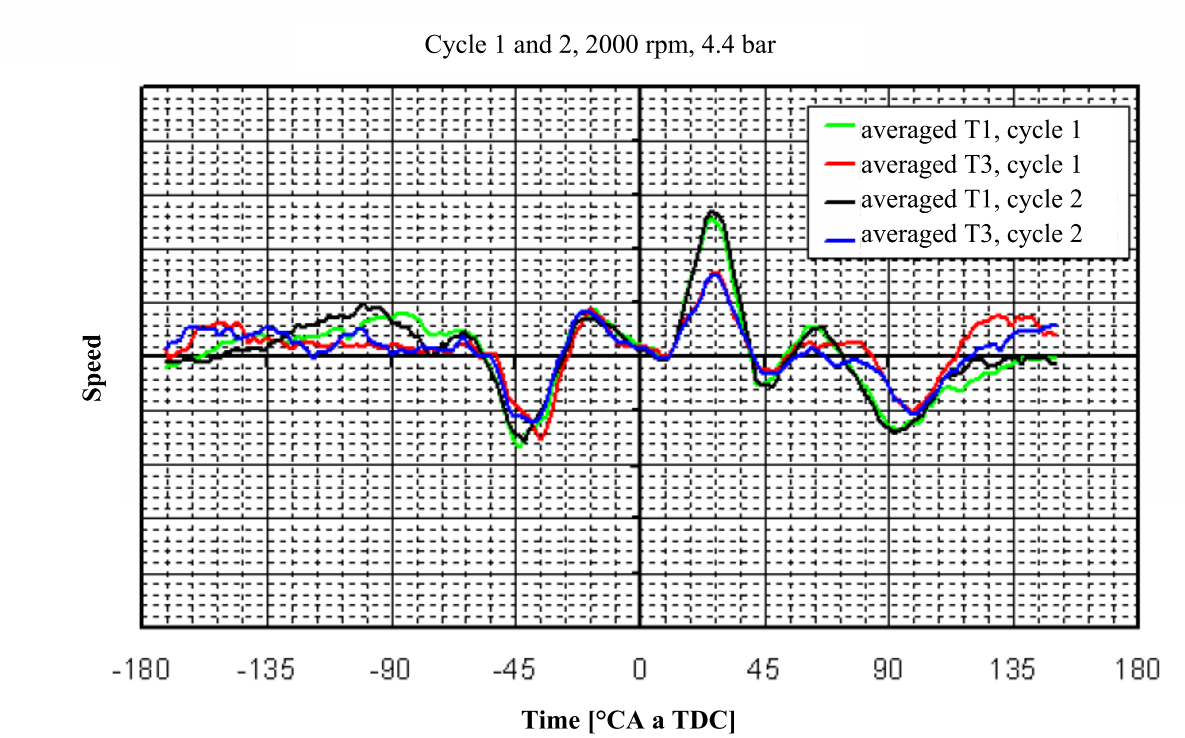


Fig. 6: Time-resolved tangential velocity at 2000 rpm, 4.4 bar

Summary

As we know with our report in [3] this is the first time that the behaviour of the 2-phase flow of gas and oil is visualised in the entire annular cooling-gallery of a piston and that the velocity of the oil is measured.

This is achieved by applying the PIV algorithm on the structures of the surface of the oil. A tracer in the gas or in the oil is not used. This technique is called Boundary-PIV (B-PIV) or 2-Phase-PIV (2-P-PIV).

- The flow velocity of oil in the cooling gallery of a piston can be measured with an optical high-speed technique.
- Increasing oil injection pressure do not leads to a higher flow velocity in the cooling gallery.
- The tangential velocity component caused by the piston velocity or acceleration are time-resolved analysed with a resolution of 1°CA.

References

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