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MESH LESS MODELING OF A PRESSURE WAVE SUPERCHARGER

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Abstract: *This paper is a simulation analysis using a mesh less modeling with Lattice Boltzmann method of the evolution of the pressures along the wave rotor channels for the exhaust gases and for the fresh air. The simulation of the process at the contact surface of the two fluids is provided in order to show the interaction of the high energy fluid with the low energy fluid. The simulation was modeled to match data, such as pressures, mass flows, usually measured in real engine on pressure wave supercharging. Results were obtained at different range of operating conditions aiming a high boost pressure into the intake, or the exhaust manifold. The LBM assures native unsteady 3D simulation only for the fluid domain. The velocity, pressure and temperature fields are presented including 3D effects with good agreement response with measurements.*
Keywords: *wave rotors, pressure wave supercharging; internal combustion engines, LBM*

1. INTRODUCTION

Superchargers are turbo-compressors positioned on the intake side of the engine to increase the air pressure at the inlet to the engine cylinder. By using mechanical overload, the improvement of the thermal efficiency of the Internal Combustion Engine(ICE) is limited, because part of the effective power of the ICE is consumed to drive the compressor [1-2]. Another conventional approach to increasing the suction pressure is exhaust gas turbines, which use the exhaust energy of the IC engine to drive the suction compressor. Turbochargers are the most widely used solutions for car manufacturers to produce a useful boost because they have several advantages. For example, higher thermal efficiency because the power of the compressor comes from the energy of the exhaust gas, rather than from the efficient functioning of the engine.

Other constructive alternatives for supercharging manage to overcome the shortcomings of the engine turbocharger. One alternative is the pressure wave supercharger (PWS). Pressure wave aggregates, known also as wave rotors, use shock waves to transfer energy directly between fluids without mechanical components, thus having the potential to increase efficiency [3]. In a PWS, the interaction between high pressure gas and high temperature gas and low pressure and low temperature air increases. In short, hot gases produce a shock wave that extends through the channels and compresses the fresh air. The quick response to engine torque for the full range of engine speeds and the intake air pressure are reasons to consider PWS a good ICE supercharging option for vehicles.

2. PWS OPERATING PRINCIPLE

As operating principle, the PWS is placed in tandem with the ICE within the thermodynamic cycle. PWSs' principle of operation is based on the fact that if two fluids having different pressures are brought into direct contact in long narrow channels, equalization of pressure occurs faster than mixing [4-7].

The channels are shaped longitudinally into a rotor (Fig. 1), called "cell rotor" that rotates between two fixed casings, called end plates. The fluids entering the PWS are the high-pressure exhaust gases (HPG) coming from the ICE and the low-pressure air (LPA). As the thermodynamic and pulsatory phenomenon occurs inside the channels, the resulting fluids leaving the PWS are low pressure gases (LPG) that have an expansion process into the channels and the compressed air (HPA) leaving the PWS is at a higher pressure.

Figure 2 shows the interaction between the components of a four port PWS. The form, dimensions, number and position of ports vary for different applications [7]. Since the end plates that include the ports have fixed positions, the channel ends of the rotor are exposed alternatively to the ports, allowing the fluids flow through the channels. Thus, the compression and expansion waves are initiated within the PWS channels, the entering exhaust hot gas generates shock waves that evolve along the channel and compress the fresh air.

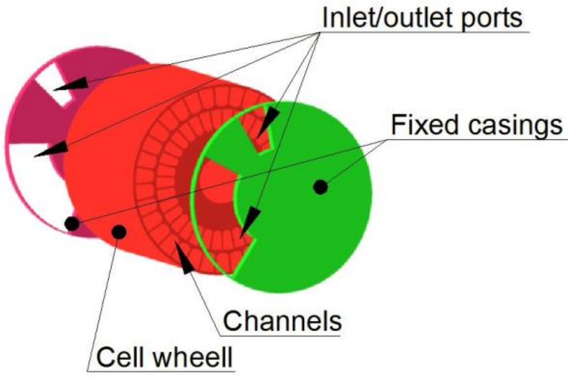

Figure 1: Components of a pressure wave supercharger

PWS design shown in Fig. 2 corresponds to reverse flow - when each flow (gas or air) exits on the same side (inlet and outlet ports are placed on the same end plate). The analysis in this paper is made on a PWS with reverse flow.

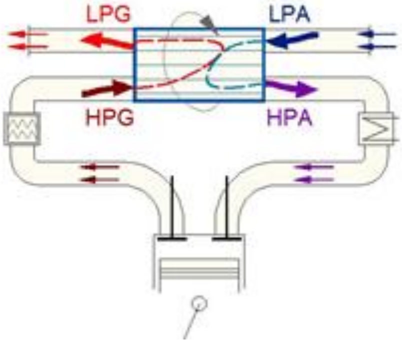

Figure 2: PWS reverse flow configuration

3. NUMERICAL MODEL

Numerical modeling using a 3D CFD model using FEM for PWS was used in paper [4]. The 3D approach showed the distribution of the velocity, pressure and temperature field in the entire modeled volume. The method involves a consistent calculation effort, even if the fluid is considered inviscid or in stationary state, due to the large number of finite elements used. This paper created a three-dimensional numerical model using the Lattice Boltzmann Method. The method was chosen because it is implicitly non-stationary and allows native modeling of rotational motion. The implementation of the LBM method in XFlow 2013 made possible the very realistic simulation of the possible conditions in the PWS channels. The 3D-PWS channels in the rotor are modeled using the basic dimensions for the CX-93 pressure wave rotor. The geometry was created in 3D using AutoCad (Fig. 3) and was imported into XFlow. The numerical model resulting from some imported geometry repair operations is shown in Fig.4 and consists of 42839 D3Q27 elements.

The rotor material used in modeling was considered steel and the fluid used was air. For air it was considered as compressible gas, and the specific heat, thermal conductivity and the viscosity were considered as temperature dependent.

An implicit solver model of XFlow was used, coupling the conservation and momentum equations with the energy equation and the flow was treated as turbulent and time dependent. To simulate the PWS behavior in the rotating machinery model a fixed rotational speed of 12500 s^{-1} was used.

The boundary conditions at inlet and outlet ports were set up as: a pressure, temperature inlet on the hot side of the inlet gases duct, and a pressure and temperature inlet at the cold side for fresh air inlet duct. The PWS channels and the ports were initially assumed to be filled with air at a reference constant pressure and temperature. The entire rotating domain containing fluid an axial motion was set up with the rotational speed n.

The model was resolved using single phase fluid, resolving both momentum and energy equations, with enabled viscous term in energy equation. The equation of state for air is used as Boussinesq state equation model. For viscosity the Sutherland model was used. The solution used for turbulence modeling is the Large Eddy Simulation (LES). This approach introduces an additional viscosity, called turbulent eddy viscosity to model the subgrid turbulence. The LES scheme uses the Wall-Adapting Local Eddy viscosity model, that provides a consistent local eddy-viscosity and near wall behavior.

The near wall treatment in boundary layer uses a generalized law of the wall that takes into account for the effect of adverse and favorable pressure gradients as presented in [8].

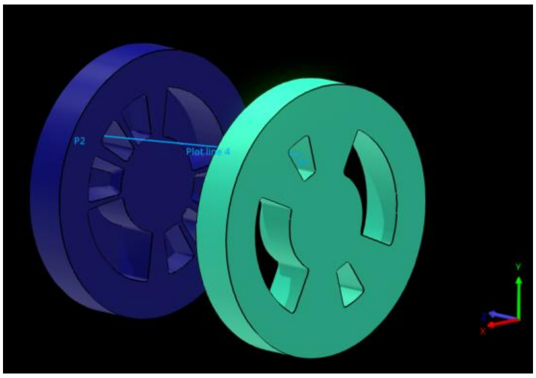

Figure 3: PWS cold(blue) and hot(green) side geometry

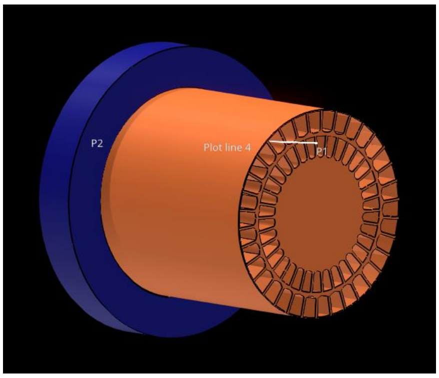

Figure 4: PWS rotor geometry

The boundary conditions are presented in Table 1.

Table 1 Entry data for the model

Property	Value
Static cold-side inlet pressure ($P_{1,0}$)	$0.96 \cdot 10^5$ Pa
Static cold-side inlet temperature ($T_{1,0}$)	313 K
Static hot-side inlet pressure ($P_{2,0}$)	$2.92 \cdot 10^5$ Pa
Static hot-side inlet temperature ($T_{2,0}$)	721 K
Air specific heat ratio (k_{air})	1.4
Air specific gas constant (R_{air})	287 J/kg K
Channel length (L)	93 mm
Rotor diameter (D)	93 mm

3. RESULTS

The results obtained with the LBM model described above are presented below. The velocity distribution in PWS channels in contour plot is presented in Fig. 5. The temperature field is presented in Fig. 6. The pressure distribution for a single PWS channel connecting exhaust gas inlet and compressed air outlet is presented in Fig. 7.

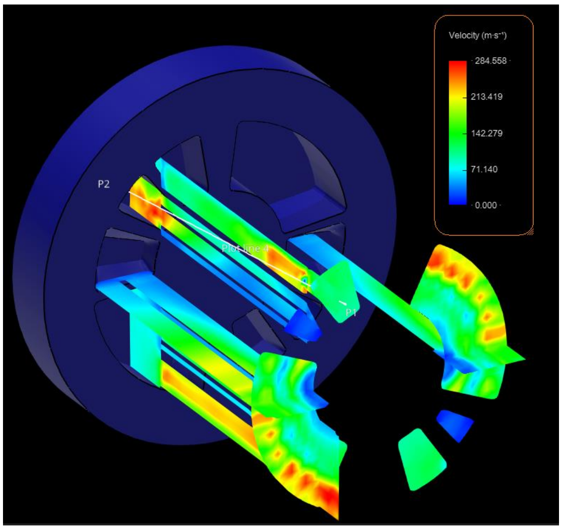

Figure 5: Velocity field for 3D model using 3 cut-planes (XY, YZ and XZ).

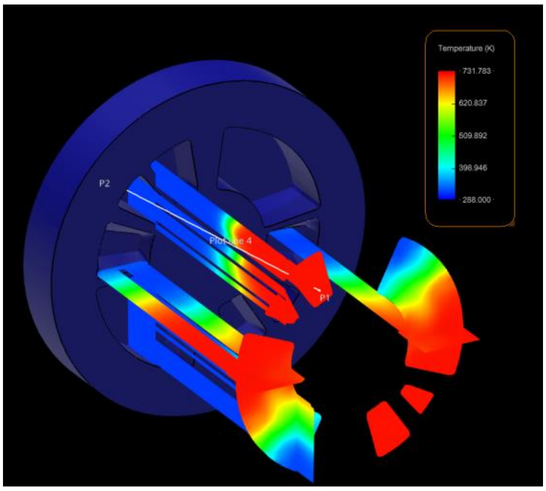

Figure 6: Temperature field for 3D model using 3 cut-planes (XY, YZ and ZX).

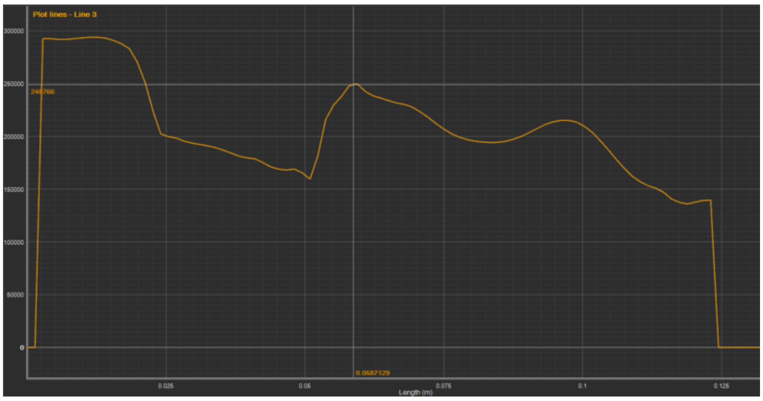

Figure 7: Pressure distribution for a single channel.

From the simulation point of view, the model shows the non-uniform of velocity, thermal fields. The velocity field as in Fig. 5 shows that the variations of velocity in channels, as well in the output exhaust gas ports and output compressed ports were quite large from 70 to 284 m/s, depending on the position of the rotor channels. The temperature field, as can be seen in Fig. 6, is also non-uniform along the rotor case. The main result for temperature field is the fact that the interfaces of air-exhaust gases do not reach the cold side, and it is remain almost near to the hot side (exhaust gases). The pressure evolution along channel is presented in Fig. 7, and shows that the compressed air is evacuated from PWS with a value of 1.47 bar, witch correspond to a 1.53 compression ratio.

3. CONCLUSION

Introducing a wave rotor in the ICE supercharging reduces the baseline compressor pressure ratio and the exit temperature of the compressor. Furthermore, this may reduce the compressor diameter and rotational speed which results in reduced mechanical and thermal stresses and relaxed design constraints.

The numerical results presented here encourage the idea that at microscale compression by shock waves may be more efficient than by conventional centrifugal compressors. However, the experimental results will be useful for further validation of the presented model with data considering variable rotational speed and experimental data.

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