Numerical Analysis and Semi-Optimisation on Water Jacket for Reciprocating Compressors

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Abstract

Numerical analysis and semi-optimisation of the water jackets have been performed for the specific reciprocating compressors.

More intensive and controlled liquid cooling of the reciprocating compressors can increase operational life, efficiency and reduce the emission. The emission usually comes from the oil evaporation, which is a function of the cylinder wall temperature.

The main goal of the numerical analysis is to determine the location of the hot spots in the inner side of cylinder (due to the inhomogeneous cooling flow field) and make a proposal for further optimisation.

1. Introduction

Nowadays, reciprocating compressors are widely used in pneumatic systems with different operational goals. In transportation point of view, one of the most widespread applications is in the brake system of trucks and railways. The mechanism of such kind of compressors requires appropriate lubrication, although significant effort has been made to develop oil free compressors. However, the recent status of today’s researches can not allow them for serial production purely economical point of view.

The engines of modern vehicles is rather compact, supplying of cooling air requires higher amount of energy with less efficiency compared with liquid cooling. Hence, nowadays, the liquid cooled compressors are widely spread. In order to optimise low oil carry over due to hot spots in the cylinder wall and so improve cooling efficiency, the water jacket should be designed and optimised by fluid dynamic point of view.

2. Numerical Analysis of Water Jacket

3D numerical analysis has been performed for modelling flow physics in the water jacket of the compressor in case of single and twin cylinder.

2.1 Conditions

The cooling liquid is ethylene glycol – water mixture. The mixture volume rate of the liquid is 52-48 %. The isothermal (T=80^{o} C) and stationary analyses have been performed at 2, 4, 6, 8 and 10 L/min flow rate.

2.2 General Parameters

The main parameters of the glycol – water mixture is following:

Mixture rate : 52-48 %
Operational temperature : 80^{o} C
Density: : 1045 kg/m^3
Specific heat : 3490 J/kg/K
Thermal conductivity : 0.39 W/m/K
Dynamic viscosity : 0.00105 kg/m/s
Molecular weight : 40.9237 kg/kg/mol
(M_{H2O}=18.0152 kg/kg/mol, $M_{HOCH2CH2OH}$=62.07 kg/kg/mol)

2.3 Geometry, Meshing and Results

The initial geometry has been given as IGES file. Gambit program was used for volume decomposition and meshing. The geometry, hybrid mesh and results are found in figures 1-11 starting with water jacket of single cylinder (figures 1-6) with inlet volume flow of 10 l/min. The sequence is the same for water jacket of twin cylinder (figures 7-11) with inlet volume flow of 2 l/min. Concerning the mesh, finer distribution was defined at specific locations, where high gradient flow field were expected. The cell number is 541989 in case of water jacket for single cylinder and 465949 in case of water jacket for twin cylinder. The number of iterations was 1000, which corresponds to 10E-4 – 10E-7 residuals. The dimension of pressure (relative to the reference (101325)) is [Pa] and the velocity is the magnitude of the velocity vector with dimension of [m/s] in legends.

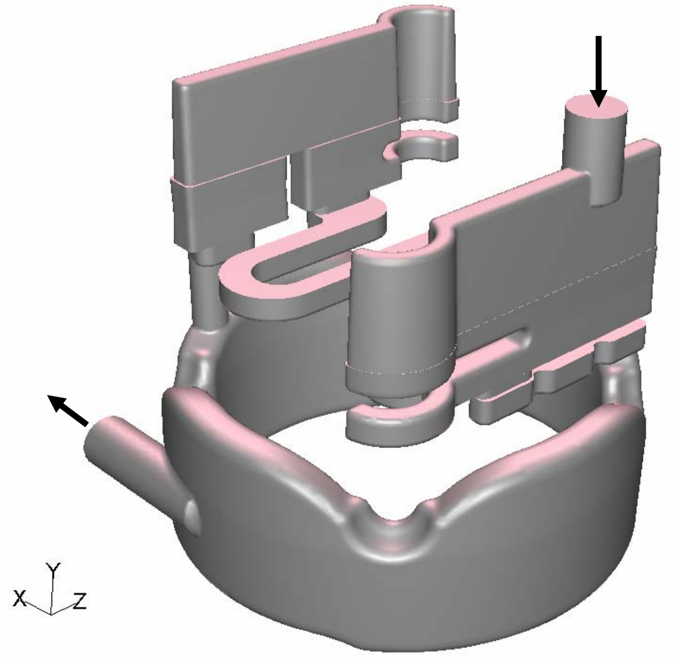

Figure 1. Geometry of the water jacket (single cylinder)

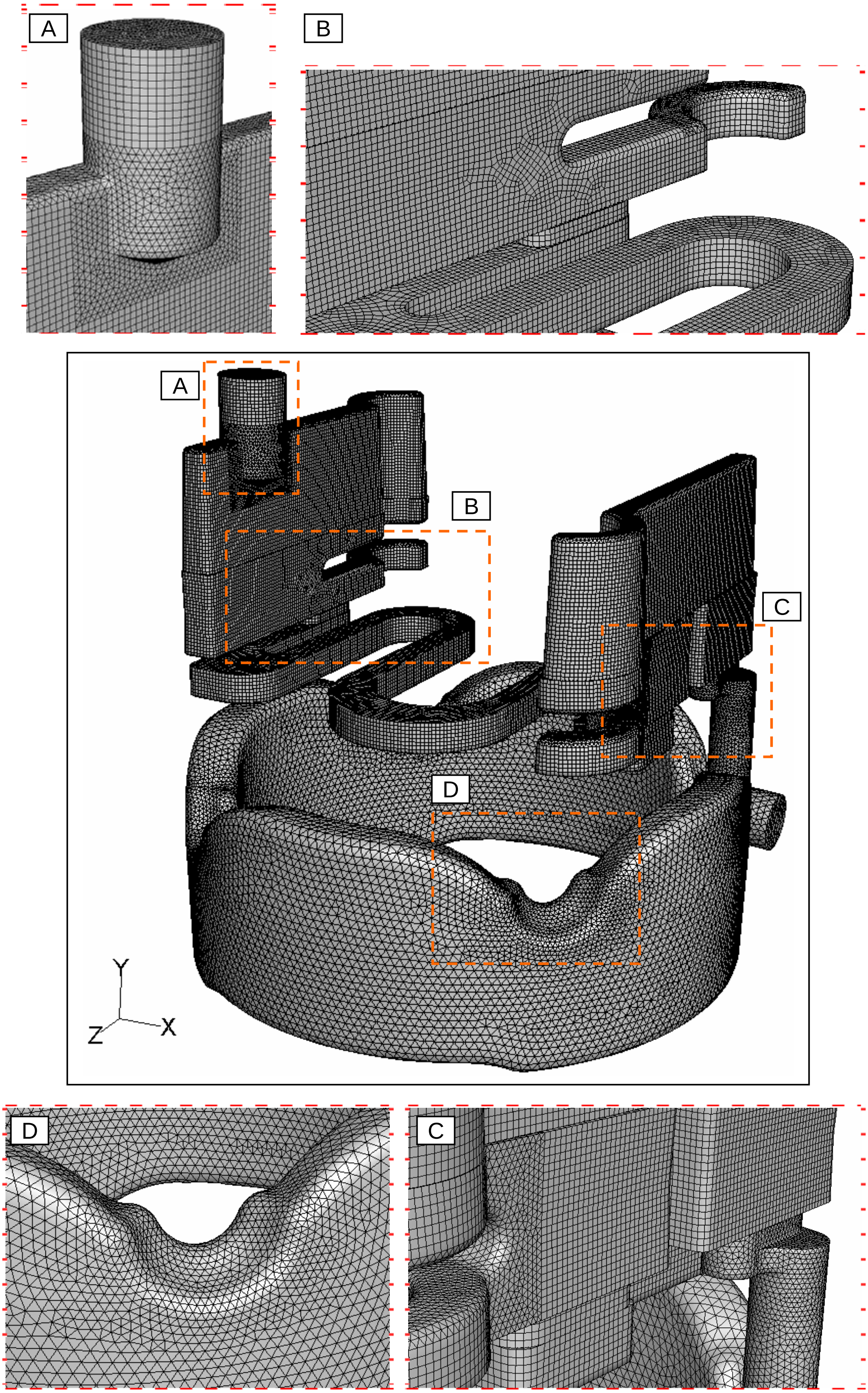

Figure 2. Mesh of the water jacket (single cylinder)

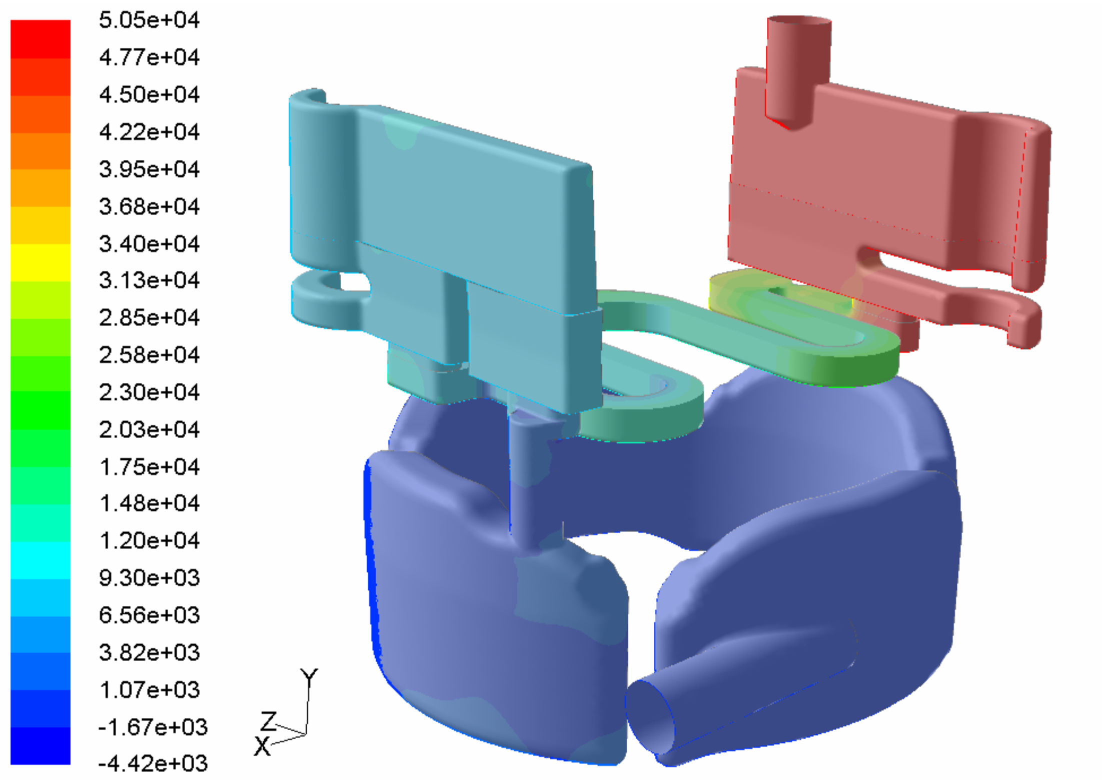

Figure 3. Pressure distribution on the wall at 10 l/min in the water jacket (single cylinder)

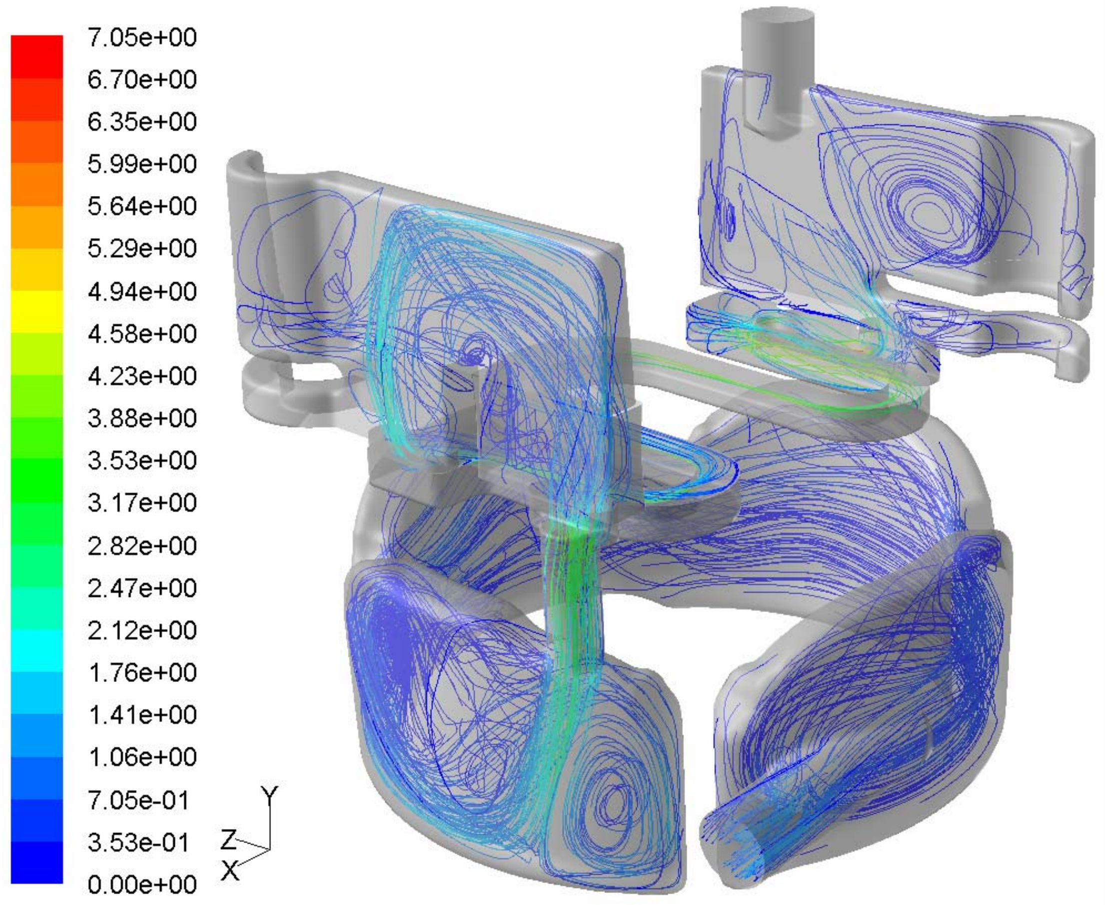

Figure 4. Streamlines (colored by velocity) in the water jacket (single cylinder) at 10 l/min

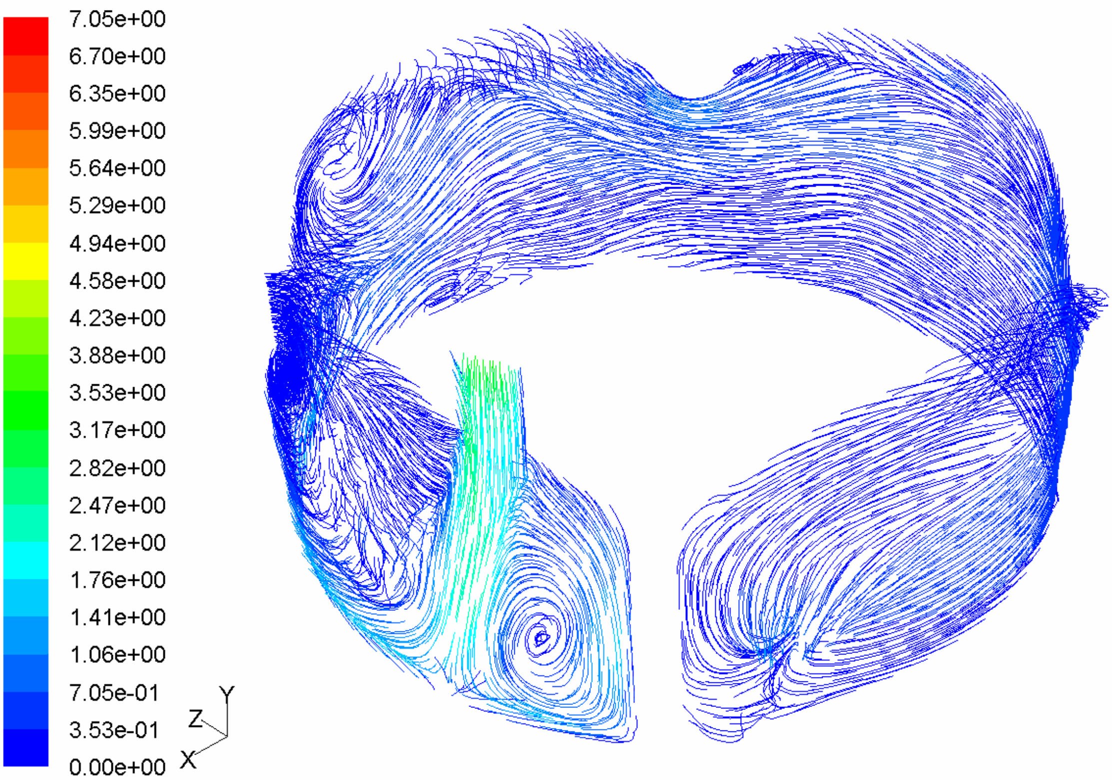

Figure 5. Streamlines (colored by velocity) at the mid-span plane of the cylinder water jacket (single cylinder) at 10 l/min

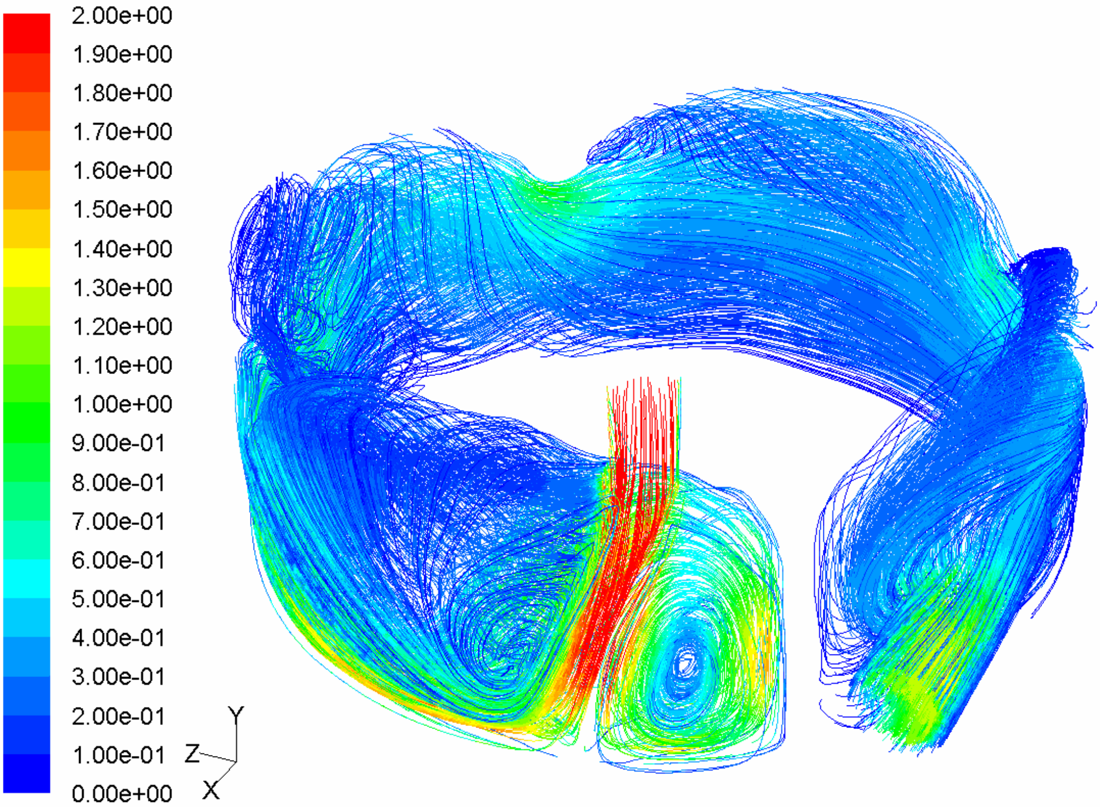

Figure 6. Streamline-pattern (down-scaled coloring by velocity) in the cylinder water jacket (single cylinder) at 10 l/min

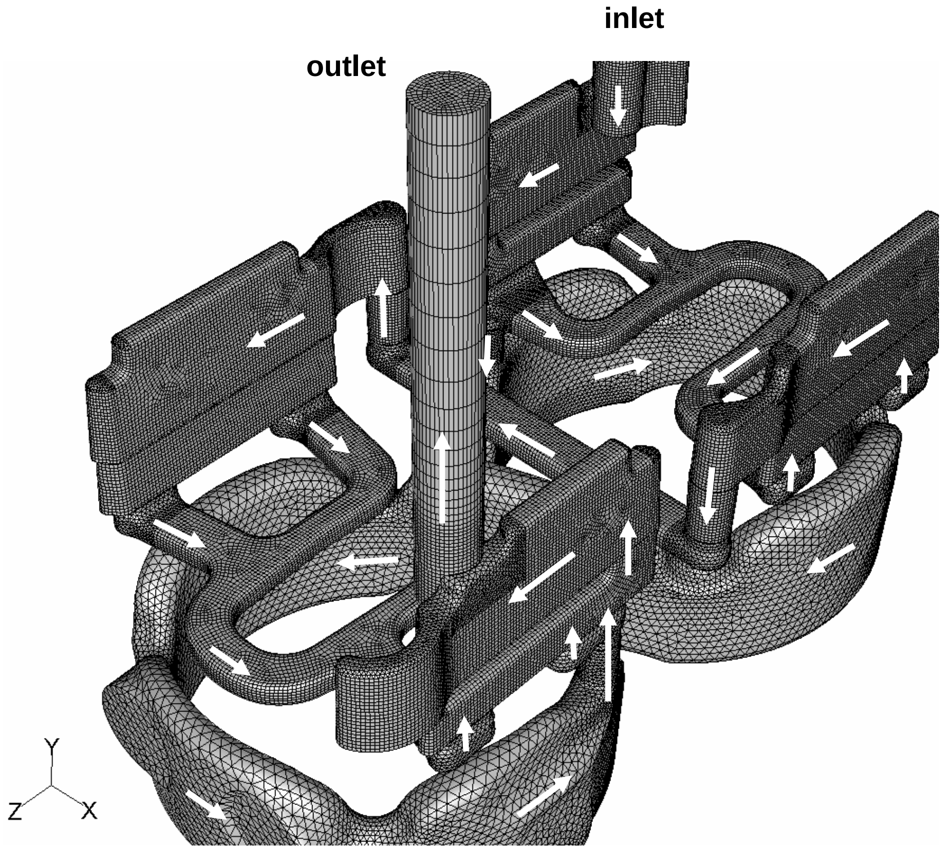

Figure 7. Geometry and hybrid mesh of the water jacket (twin cylinder) with flow directions

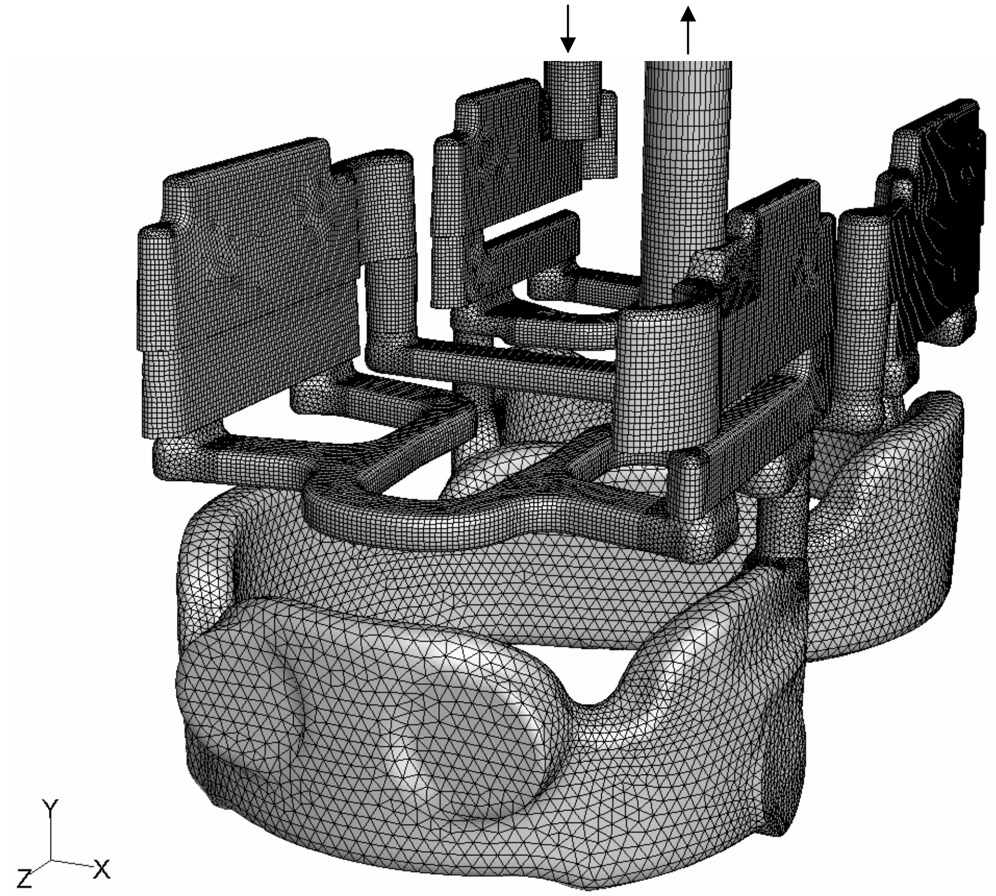

Figure 8. Geometry and hybrid mesh of the water jacket (twin cylinder)

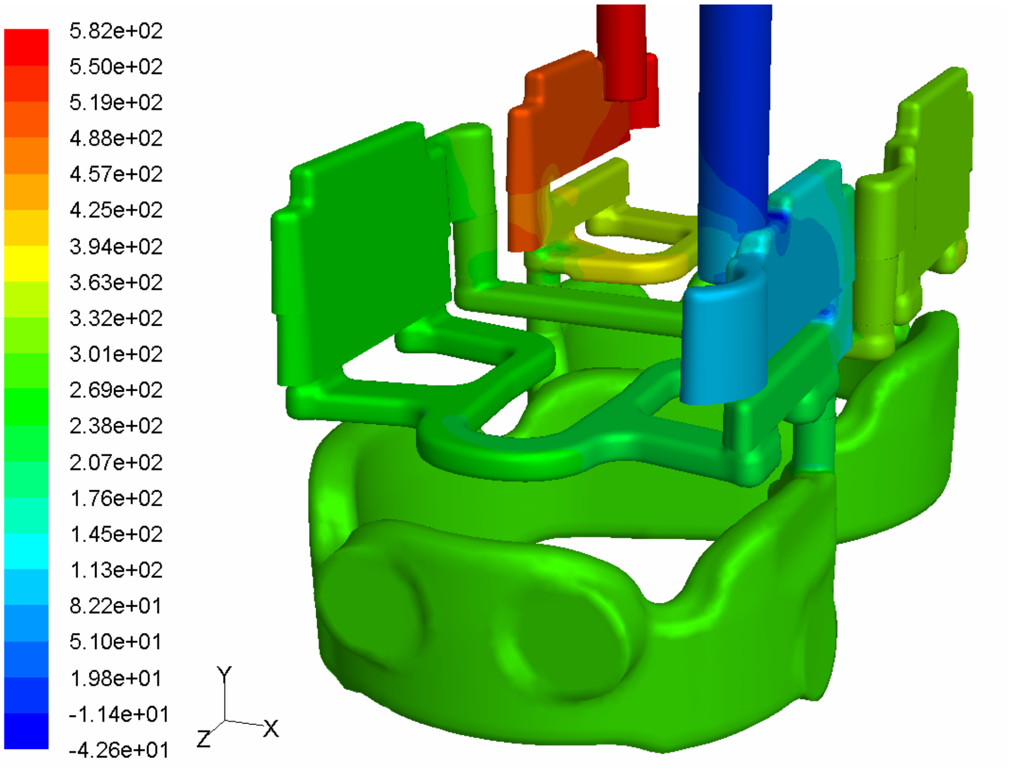

Figure 9. Pressure distribution on the wall at 2 l/min in the water jacket (twin cylinder)

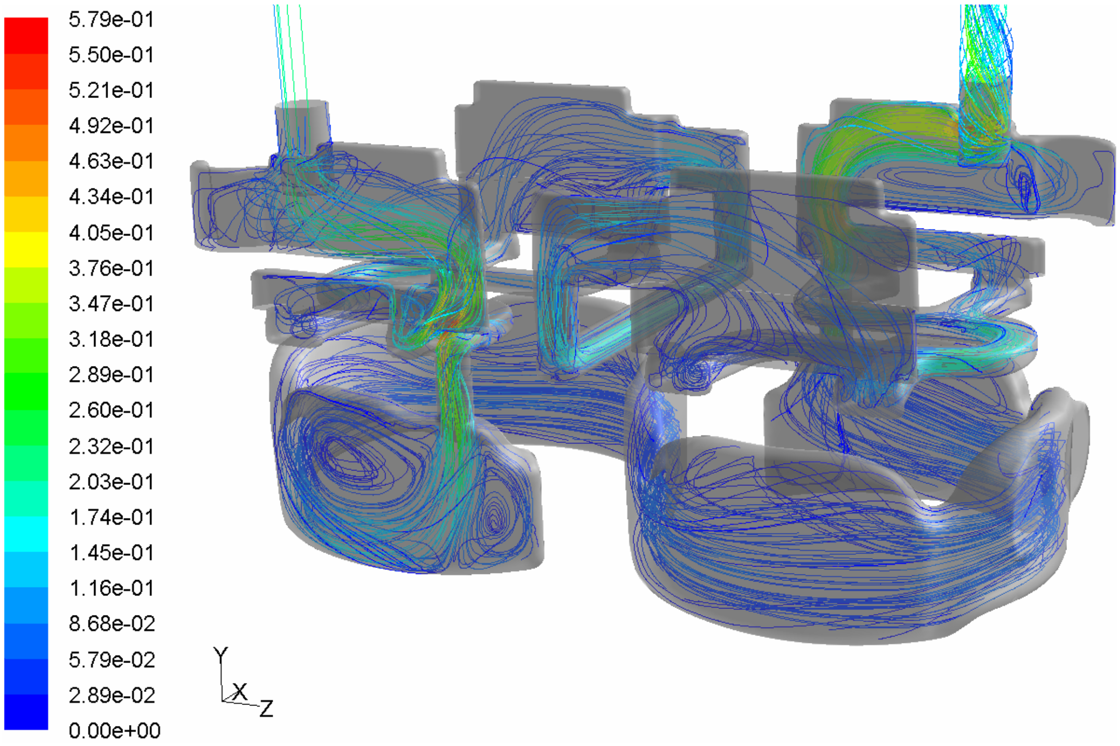

Figure 10. Streamlines (colored by velocity) in the water jacket (twin cylinder) at 2 l/min

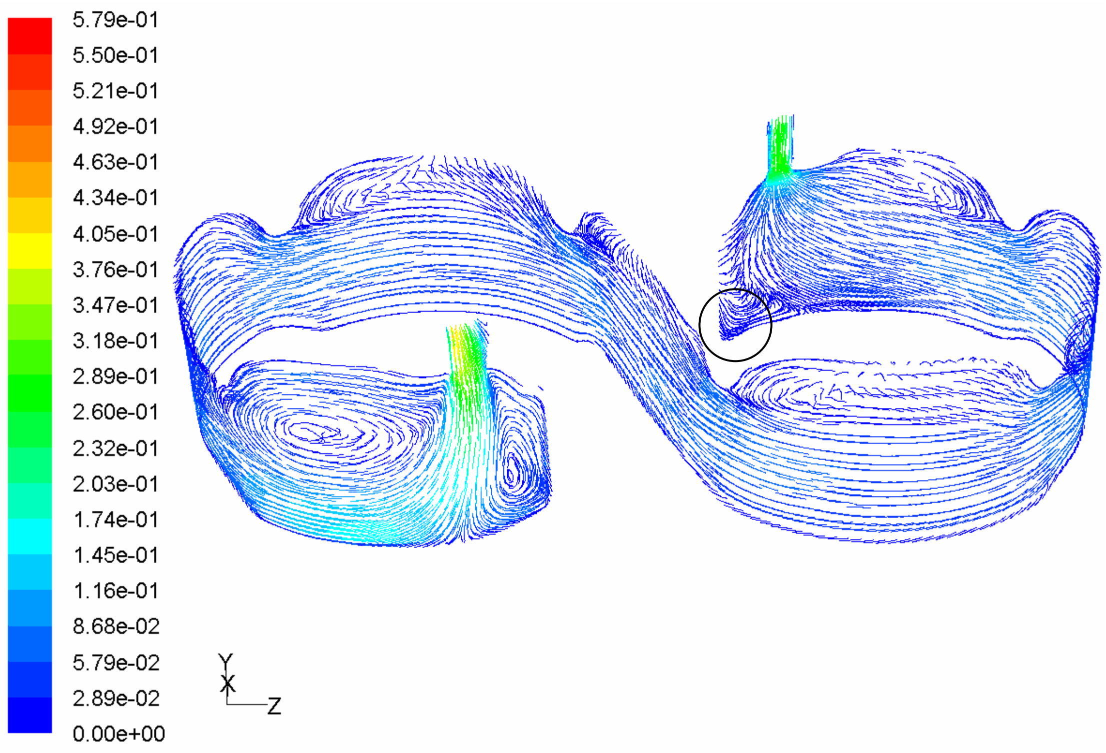

Figure 11. Streamlines (colored by velocity) at the mid-span plane of the cylinder water jacket (twin cylinder) at 2 l/min

There is no significant difference between the different type of turbulence modelling and wall treatment, which has also been investigated. Hence, the k-epsilon, RNG differential viscosity model, swirl model and enhanced wall treatment options were used.

Completing the analysis of the water jacket of compressors, it can be generally concluded that the cross sections, geometry and so the local pressure gradient has a significant effect on the mass or volume flow rate distribution in the manifolds of water jackets. High intensity separation bubbles are formed around the inlet jet of cylinder water jacket (e.g. figures 4, 5, 6, 10 and 11) and in some cases behind the bump for cylinder–head bolt (e.g. figures 5 and 11). The strong diffusivity can be decreased by using guiding vanes, ribs and/or controlled diffusion geometry.

Quantitative analyses also have been made for determining static pressure drop and loss coefficient over the water jackets. The equation of loss coefficient is following:

$$\omega = \frac{p_{in}^{to} - p_{out}^{to}}{p_{in}^{to} - p_{in}^{st}} \qquad (1)$$

The loss coefficient is shown in the function of Reynolds number at the inlet duct:

$$Re_d = \frac{vd}{\nu} \qquad (2)$$

The pressure drop of the water jackets are shown in the function of volume flow rate and it is found in figure 12.

where d is the diameter of the inlet duct, v is the average inlet velocity and ν is the kinematic viscosity. The diagram is found in figure 13.

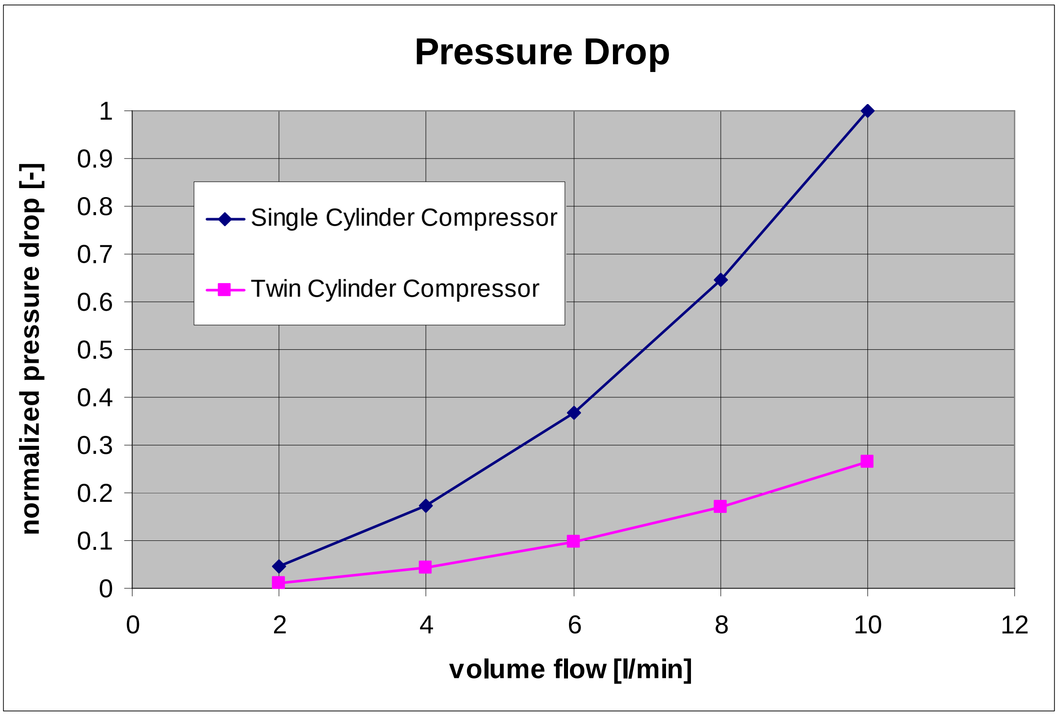

Figure 12. Static pressure drop of the water jackets

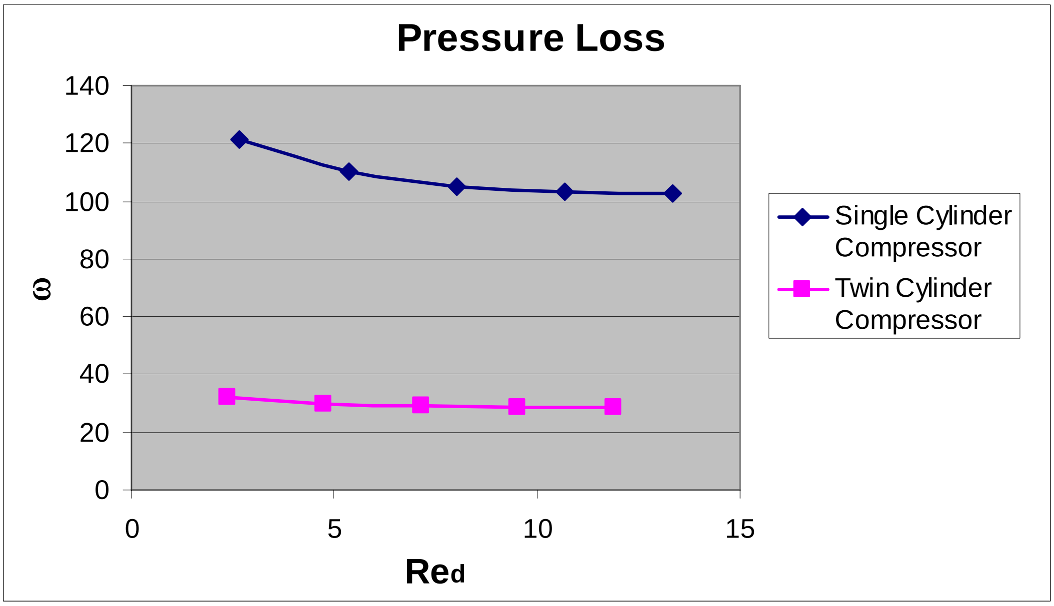

Figure 13. Loss coefficient in the function of Reynolds number

2.4 Conclusions

It can be generally concluded that the water jacket of single and twin cylinder compressors may require further optimisation in fluid dynamics point of view. The flow fields are nearly homogeneous except some specific locations, in where separation bubbles were observed.

Pressure loss in the water jacket has a significant effect on the engine performance and so it is relevant to reduce it. Loss coefficients show significant difference between the compressor water jackets of single and twin cylinder (see figure 13). The cross sections of the manifolds, pipes and volumes, the contractions of the connections and the geometrical structures of the flow field determine the pressure drop in the water jacket. In order to improve design specifications at compressor of single cylinder, the sharp edges and corners should be rounded of and chamfered, while the cross sectional areas should adopt to the homogeneous distribution of the main velocity into the direction of the main flow. The magnitude of the velocity vector is much higher in case of single cylinder compressor compared with twin cylinder ones in the manifold around the valves (see figures 4 and 10). Hence, cross section area increment has been proposed for manifold around the valves for single cylinder compressor.

The most critical part of the water jacket geometry is a gap between the ends of cylinder water jackets, where they are open (see figures 5 and 11) in hot spots development point of view. The other crucial location is around the inlet section of the cylinder cooling. High intensity separation bubbles are observed next to the inlet jet stream (see figures 4, 5, 6, 10 and 11). The recirculating flow fields are due to the high adverse pressure gradient caused by high geometrical diffusion. The low intensity mixture rate in the core of the vertices can reduce heat transfer between the cylinder wall and the cooling fluid. Controlled diffusion geometry (see figure 14) has been proposed to improve the cooling efficiency. The overall diffusion of the geometry has been determined on such a way that the flow has been kept below the separation limit. The other possibilities is to overcome the problem to implement flow guiding vanes, ribs, using split manifolds or amplify secondary flow by eccentric inlet duct (see figures 15 and 16).

Considering the deposit or sludge, the most critical section is near to the outlet of water jacket with two cylinder (see figure 11 denoted by a circle). Outlet duct displacement has been suggested to reduce the risk of deposit. One possible solution is found in figures 5 and 6, similarly with compressor of single cylinder.

The cooling flow field is nearly uniform at the axial position of backward and forward stroke, hence the local temperature increment, caused by the eliminated oil film, is cured properly.

In some cases separation bubbles were also observed in the cylinder water jacket between bumps of cylinder–head bolts (see figures 5, 6 and 11). It is general way to decrease the high diffusivity by variable cross section (controlled diffusion channel) or applying flow guiding vanes.

Usually, the flow field optimization is constrained by mechanical limitations. Hence, it is indispensable to know the possible dimensions of the modification of the water jacket geometry.

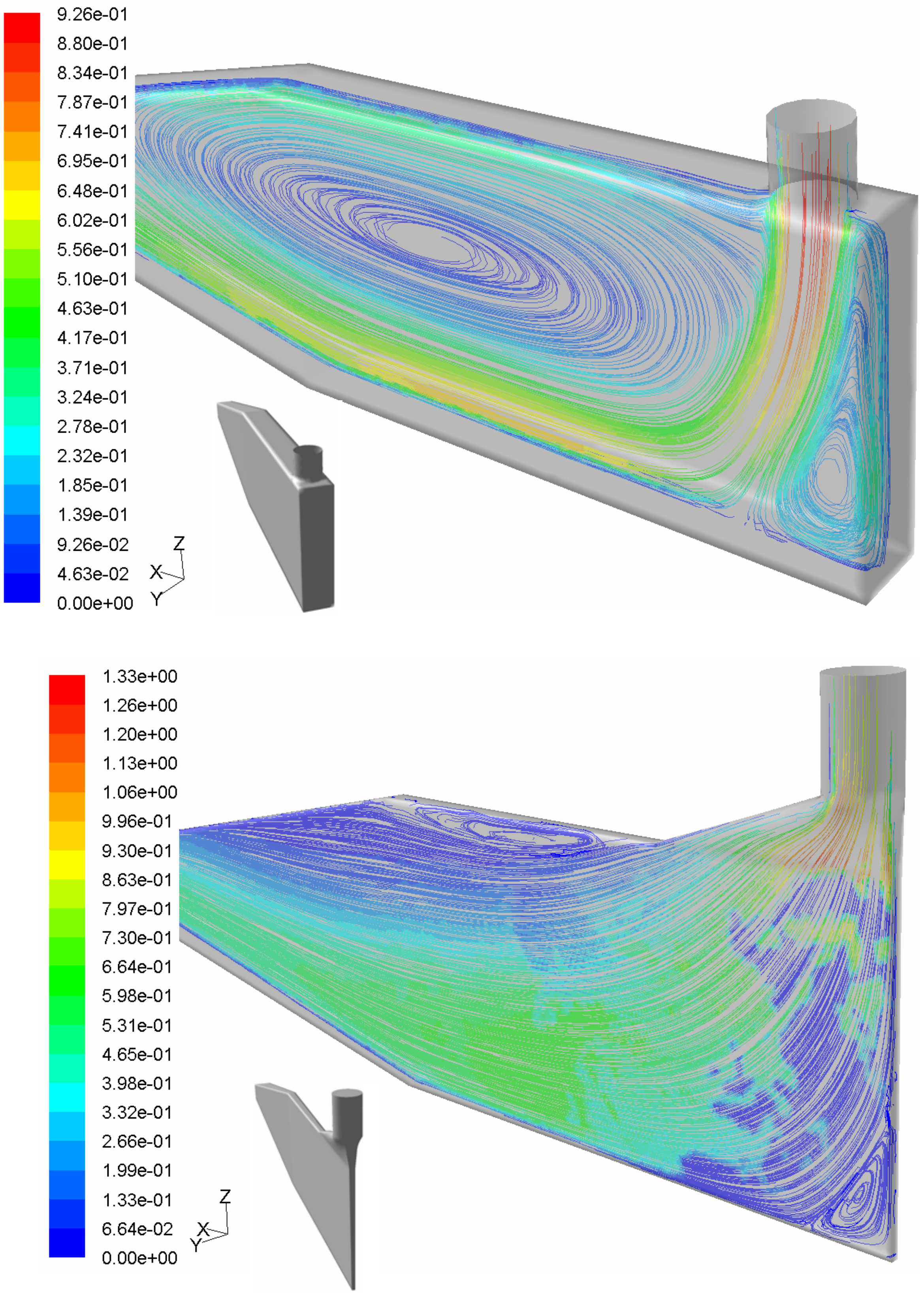

Figure 14. Original and controlled diffusion cylinder inlet design

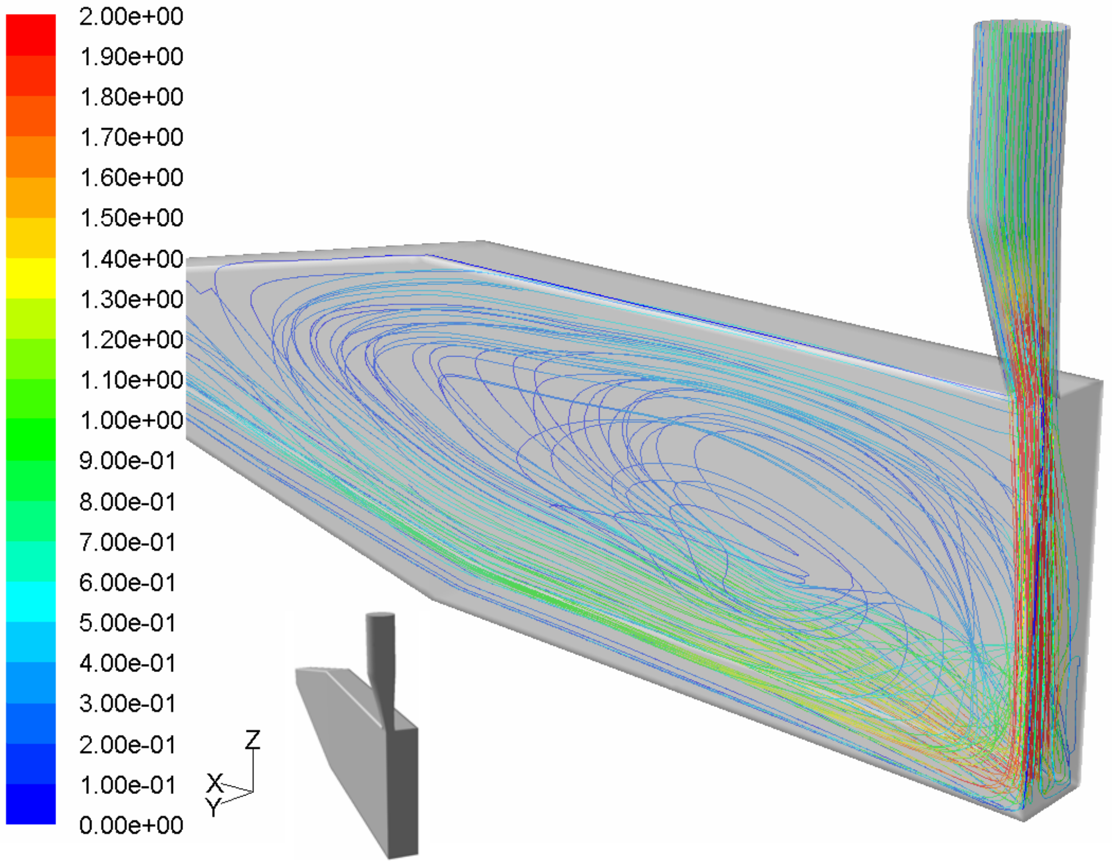

Figure 15. Eccentric inlet duct for amplifying secondary flow intensity

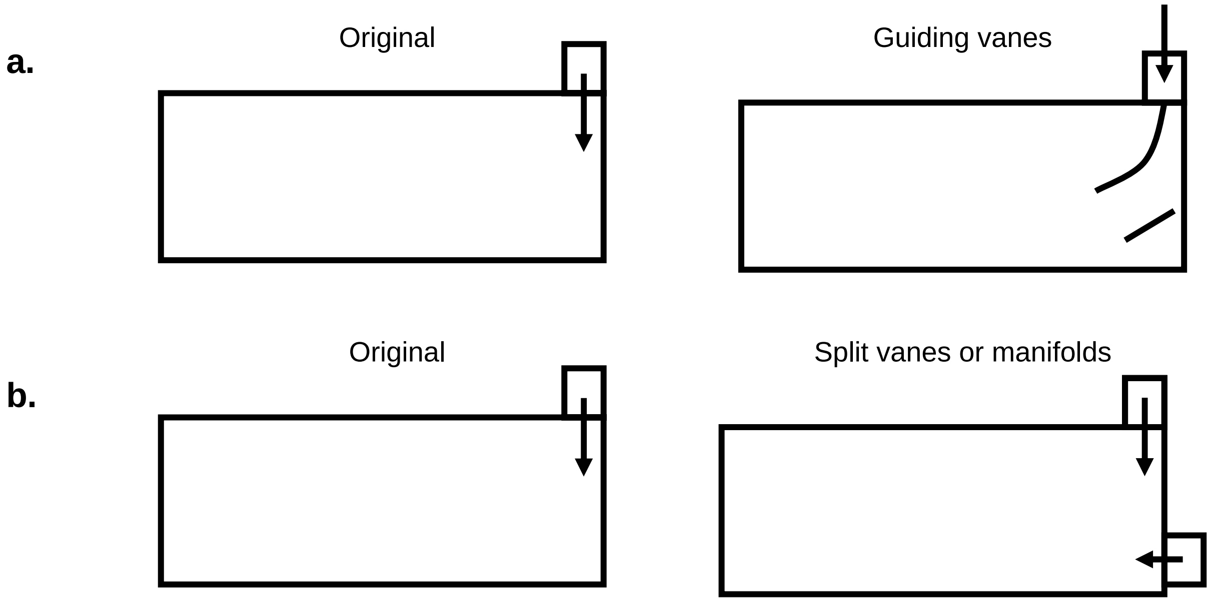

Figure 16. Improvements possibilities on damping inlet flow recirculation