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DOMAIN DECOMPOSITION METHOD FOR 3-DIMENSIONAL SIMULATION OF THE PISTON CYLINDER SECTION OF A HERMETIC RECIPROCATING COMPRESSOR

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ABSTRACT

The simulation of the piston-cylinder is a simulation in which the shape of the domain changes with time due to the motion of the piston. As it is difficult to get accurate boundary conditions at the surfaces adjacent to the gas inside the cylinder, the cylinder, the piston and the cylinder head must be included in the simulation domain.
The calculation time can be reduced significantly by applying a domain decomposition method. The fluid domain is simulated separately from the solid domains. At the interfaces, a temperature boundary condition is applied. The heat fluxes obtained from the fluid simulation are transferred to the solid domain simulation to define a substitute convection boundary condition at the interfaces. Then the interface temperatures obtained from the solid domain simulation are transferred to the fluid domain simulation as the new temperature boundary conditions for the next simulation. The iteration is carried out until the change of interface temperatures less is than 0.1°C. The convergent result is obtained by 9 iterations.

1. INTRODUCTION

Three-dimensional simulation covering the whole domain of the compressor is still a big task in the future. An intermediate way would be a three-dimensional simulation of a sub-system of the compressor. Several sub systems (sections) of the compressor, such as the suction line, the piston-cylinder system and the discharge line, can be individually considered as objects to be simulated. Concerning the simulation of the piston-cylinder system, a model with an appropriate cell size, beginning at the neck of the suction muffler to the entrance of the first plenum in the discharge line has been created (see figure 1). The number of cells, when the piston is at top dead centre (TDC), is about 250,000. It increases as the piston moves downwards and reaches the maximum number of about 1.8 million cells when the piston is at bottom dead centre (BDC). The inflow and outflow boundary conditions are prescribed pressure (Abidin and Almbauer, 2003). The main specifications of the compressor are as follows:

- electric power : 120 W
- bore : 25.4 mm
- stroke : 22 mm
- compression ratio: 85 (ratio of volume)

Several commercial softwares are able to carry out a 3-dimensional simulation of the piston-cylinder (in this case Fluent Inc. is used). The problem occurs due to a very long time to get a convergent result. With an electric motor speed of 2950 rpm, the information from the boundaries cannot be transferred to the inner side of the solid domain within only several cycles (the solid domain of the cylinder has a thickness of about 1.2 cm). Running the model on an Opteron 2000 MHz Processor (new technology of AMD generation) takes about ten days for the simulation of one cycle. Normally it takes approximately 45 minutes to get a steady result for the compressor in the experiment. Thus, it takes thousands of cycles to reach a convergent solution for the whole domain. To avoid this problem, the following domain decomposition method is proposed.

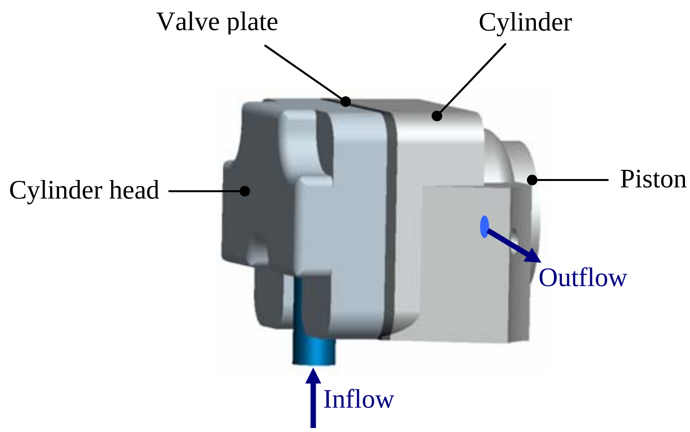

Figure 1. Model of the piston-cylinder system

2. DOMAIN DECOMPOSITION METHOD

Domain decomposition in this case means that the simulation of the fluid domain is separated from the simulation of the solid domains. The simulations of the fluid and solid domains are performed serially so that it enables a transfer of simulation results of the fluid domain to be the boundary condition values of the solid domain, or vice versa.

In addition, one cycle takes only about 0.02 second. Due to this quite short period, the transient phenomena from the fluid domain penetrate the solid material only less than 0.15 mm (Abidin, *et al.*, 2005). Based on this fact, the calculation of the solid domains is performed in steady mode. Thus, the calculation time reduces significantly. For the complete thermal simulation the calculation domain is divided into three domains, i.e. fluid, cylinder (including muffler neck, valve plate and cylinder head), and piston (see figure 2).

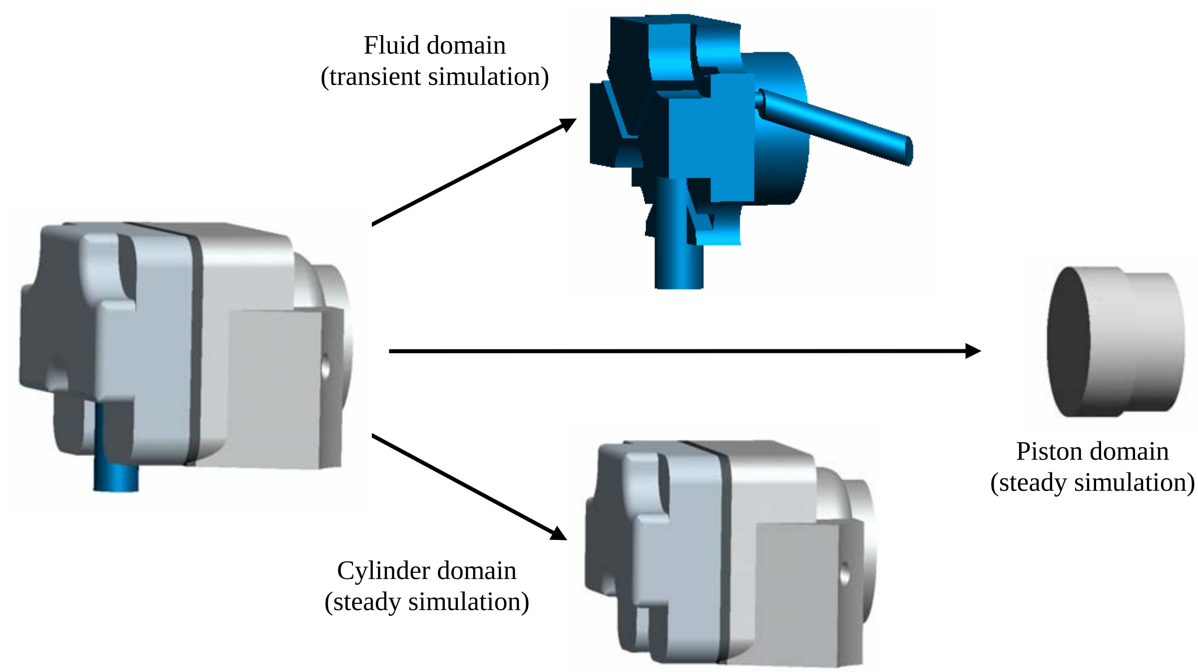

Figure 2. The domain decomposition method for the piston-cylinder simulation

There are 6 interfaces between the fluid and the cylinder domains, namely:

1. Suction port
2. Valve plate (adjacent to fluid inside the cylinder)
3. Valve plate (adjacent to fluid inside the cylinder head)
4. Discharge port
5. Cylinder liner
6. Cylinder head

Between the fluid and the piston domains, the interface is at the upper surface of the piston. Then, between the piston and the cylinder, the interaction takes place along the liner surface, i.e. between the cylinder liner and the piston sealing surface. To accommodate the expected temperature distribution from TDC to BDC, the cylinder liner surface is divided into 15 segments. Likewise, the piston sealing surface is divided into 4 segments. Every segment has a length of 2 mm except the first segment of the cylinder liner (near to the valve plate). This top segment has a length 2 mm plus 0.18 mm (0.18 mm is the distance between the valve plate and the piston when it is at TDC). When the piston is at BDC, its four segments coincide with the last four segments of the cylinder liner (see figure 3).

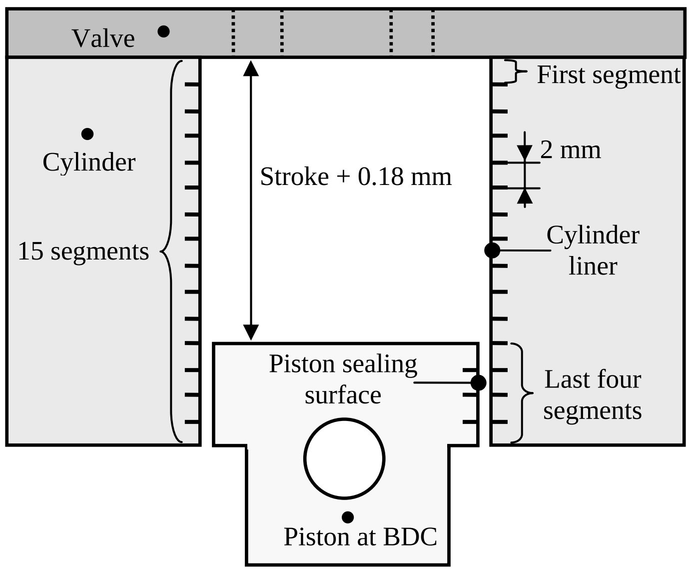

Figure 3. Segmentation of the cylinder liner and the piston sealing surface

3. BOUNDARY CONDITIONS TREATMENT AT THE WALL SURFACES

Except at the interfaces, a convection boundary condition is applied at the wall surfaces. The environment temperature is the gas temperature inside the shell (60 °C). The boundary condition at the interfaces is explained in the following sections.

3.1. Fluid Domain

For transient simulation of the fluid domain, a prescribed temperature boundary condition is applied at the interfaces. For the interfaces at the cylinder liner, a linear profile is assumed. At the beginning of simulation, these are guessed value. If the iteration has begun, these are obtained from the last simulation result of the solid domains.

3.2. Solid Domains

The solid domains consist of the cylinder (including muffler neck, valve plate and cylinder head), and the piston. From the simulation of the fluid domain, heat fluxes at the interfaces are obtained. As the simulation of the fluid domain is performed in transient mode, these heat fluxes are cycle-averaged before they are used to determine the boundary values of the solid domains.

The cylinder liner can have a contact with the fluid inside the cylinder (above the piston), the piston sealing surface and the fluid inside the shell (below the piston). Thus, its heat flux is the total heat flux from these three surfaces, namely:

$$\dot{Q}_{lin} = \dot{Q}_{cy\rightarrow g} + \dot{Q}_{cy\rightarrow p} + \dot{Q}_{cy\rightarrow gs} \tag{1}$$

This formula can be applied to each segment of the cylinder liner surface by inserting a weighting factor. The weighting factor between segment *i* and the surface *s* ($WT_{i\rightarrow s}$) is the ratio of the contact time between them and the period of one cycle. The heat transfer occurring in segment *i* of the cylinder liner can be formulated as below:

$$\dot{Q}_{lin,\,i} = WT_{lin,\,i\rightarrow g}\ \dot{Q}_{lin,\,i\rightarrow g} + \sum_{j=1}^{4} WT_{lin,\,i\rightarrow p,\,j}\ \dot{Q}_{lin,\,i\rightarrow p,\,j} + WT_{lin,\,i\rightarrow gs}\ \dot{Q}_{lin,\,i\rightarrow gs} \tag{2}$$

The heat transfer between the cylinder liner and the fluid inside the cylinder ($\dot{Q}_{cy\rightarrow g}$) can be obtained from the simulation of the fluid domain. The heat transfer between the cylinder liner and the piston sealing surface ($\dot{Q}_{cy\rightarrow p}$) is calculated by a heat conduction formulation. In the presence of a clearance, it is expected to have a lubricant layer between the piston sealing surface and the cylinder liner surface. Thus, the heat transfer which takes place in the thin lubricant layer between segment *i* of the cylinder liner and segment *j* of the piston can be formulated by:

$$\dot{Q}_{lin,\,i\rightarrow p,\,j} = A_{lin,\,i\rightarrow p,\,j} \cdot \frac{\lambda}{l}\left(T_{lin,\,i} - T_{p,\,j}\right) \tag{3}$$

where λ and *l* are the thermal conductivity and the thickness of the lubricant layer. The thickness of the lubricant layer itself is according to the clearance.
The heat transfer between the cylinder liner and the fluid inside the shell is calculated by a convection formulation. Thus the heat transfer between segment *i* of the cylinder liner and the gas inside the shell can be formulated by:

$$\dot{Q}_{lin,\,i\rightarrow gs} = A_{lin,\,i\rightarrow gs} \cdot \alpha\left(T_{lin,\,i} - T_{gs}\right) \tag{4}$$

where α is the convection coefficient between the cylinder liner and the gas inside the shell. The temperature of the gas inside the shell and the convection coefficient is obtained from experimental results.
The heat transfer at the piston sealing surface can be formulated accordingly. The piston sealing surface only has contact with the cylinder liner and the heat transfer between them is a conduction-typed heat transfer (see equation (3)). The heat transfer which occurs in segment *i* of the piston sealing surface is:

$$\dot{Q}_{p,\,i} = \sum_{j=1}^{15} WT_{p,\,i\rightarrow lin,\,j}\ \dot{Q}_{p,\,i\rightarrow lin,\,j} \tag{5}$$

3.2.1. Substitute convection boundary condition: Applying a heat flux boundary condition means that the value of heat flux is fixed at the boundary. If the heat flux is too high, there will be a significant increase of the temperature (and possibly an overshoot) in the solid calculation.

This problem can be avoided by applying a substitute convection boundary condition. The idea behind this is the fact that the heat flux also depends on the surface temperature. The heat flux coming to the first finite volume of the solid domain (cells adjacent to the fluid domain) can be treated as a temperature-dependent heat source which has a negative-slope relationship with the surface temperature (T_s), and this is formulated as:

$$\dot{Q}_{g\rightarrow s} = A_{g\rightarrow s} \cdot \alpha\left(T_g - T_s\right) \tag{6}$$

The gas temperature is calculated based on the heat flux result from the fluid domain simulation and the surface temperature from the last simulation of the solid domain. This convection boundary is applied to all interfaces except at the liner surface.

4. STEPS OF DECOMPOSITION DOMAIN METHOD

Figure 4 shows the flowchart of the calculation. The steps of the decomposition domain method are explained as follows:

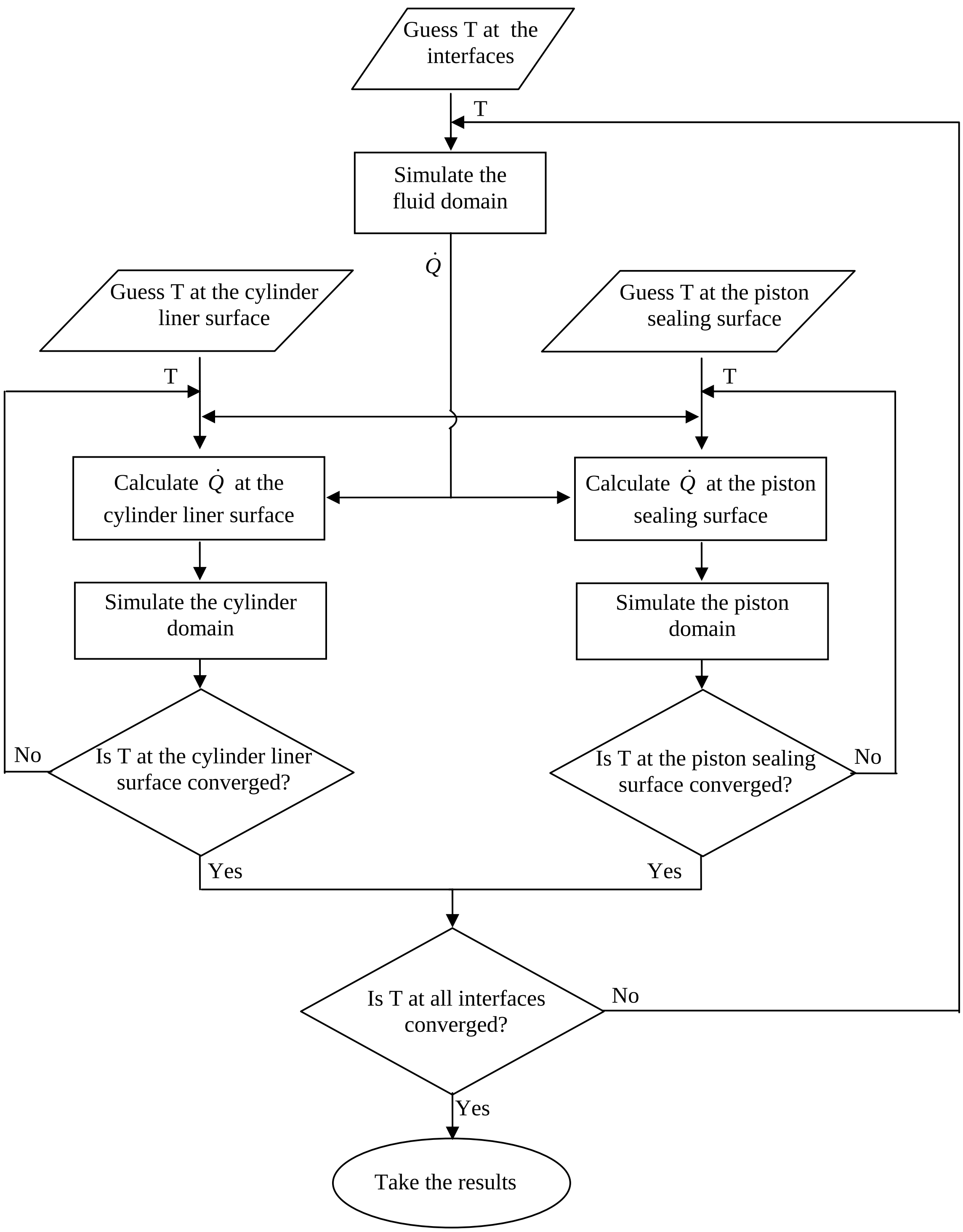

Figure 4. The flowchart of the calculation

1. A transient simulation of the fluid domain is carried out. Besides the boundary condition mentioned above, the valve lift movement is also needed to specify the movement of the valves. It is necessary to perform several cycles for the initial simulation.
2. Heat flux at the cylinder liner is calculated using equation (2). The heat flux from the fluid inside the cylinder is obtained from the simulation of the fluid domain in step 1. The heat flux from the piston and the gas inside the shell is calculated using equation (3) and (4). The temperature of the cylinder liner is guessed at the beginning or taken from previous iteration.
   Accordingly, the heat flux at the piston sealing surface is calculated using equation (5). The temperature of the piston sealing surface is guessed at the beginning or taken from previous iteration.
3. A steady simulation for the cylinder and the piston domains is carried out. The heat fluxes at the cylinder liner and the piston sealing surfaces obtained from step 2 are used as the heat flux boundary condition. At other interfaces, the heat fluxes obtained from the simulation of the fluid domain (step 1) are used to determine the substitute convection boundary conditions.
4. Temperature results are obtained from step 3. The new temperatures of the cylinder liner and the piston sealing surfaces are compared with the guessed or old temperatures. The iteration of these solid domains is carried out until the difference between the new and old temperatures of the cylinder liner and the piston sealing surfaces is less than 0.1 °C. An under-relaxation factor of 0.3 is used for this iteration.
5. The temperature results at step 4 are compared with the guessed or old temperatures which are inputted in step 1. Step 1 to step 4 is repeated again until the temperature difference for all surfaces is less than 0.1 °C. An under-relaxation factor of 0.3 is used for this iteration.

5. RESULTS

By applying this decomposition domain method, the convergent result in all domains is obtained by 9 iterations. Thus the calculation time reduces significantly. The temperature convergences at several interfaces are shown in figure 5. The values of 0^{th} iteration are the guessed value.

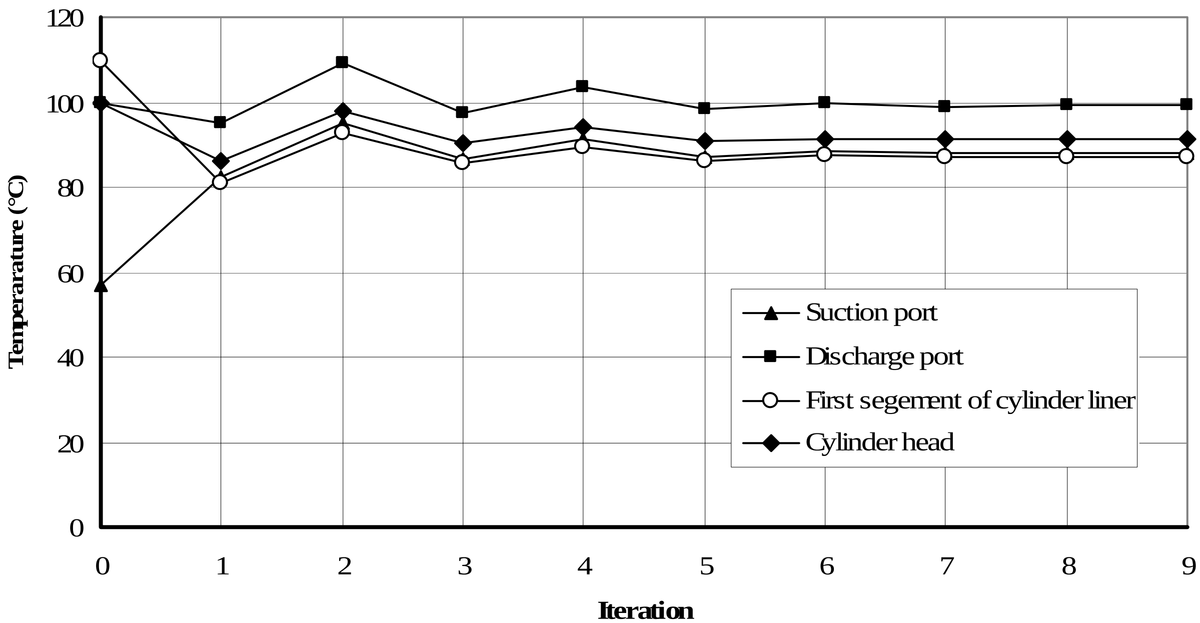

Figure 5. The temperature convergence at several interfaces

In addition, all thermodynamic properties and other parameters can be obtained at each location as well as their contours or profiles at a certain cross section area. Some of the results are presented here. Figure 6 shows the instantaneous gas pressure variation over one cycle at several zones. At 180 degree crank angle (°CA) the piston is at BDC that gives the maximum cylinder volume. In addition, the measurement of the gas pressure variation inside the cylinder in the indicator test bench is also shown. The simulation result almost fits to the experimental data except at the re-expansion phase. The re-expansion line of the simulation result lies on the right-hand side of the re-expansion line of the experiment result. This means that the expansion work in the simulation result is higher than the one in the experimental result.

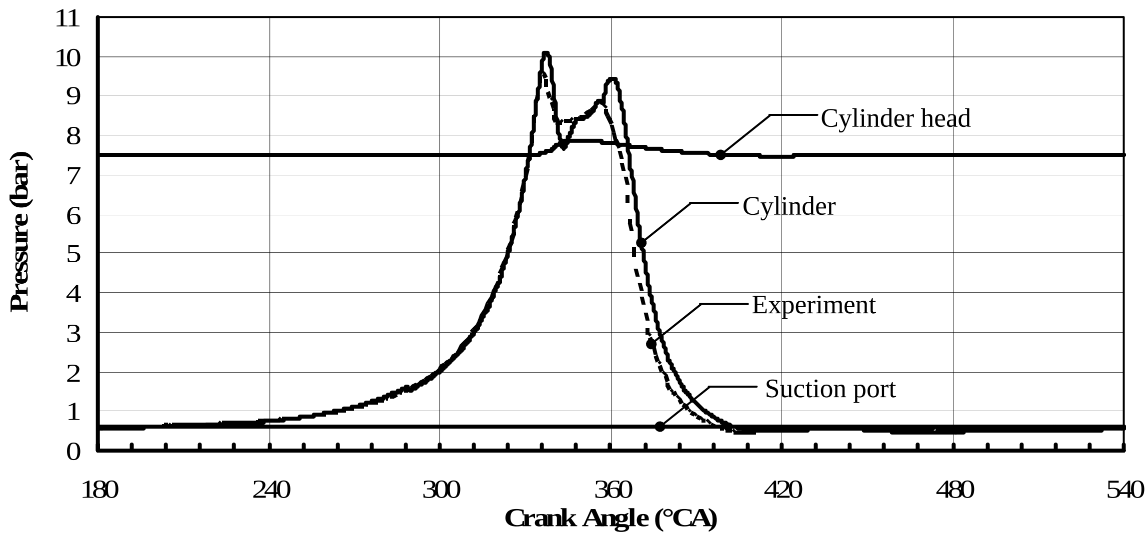

Figure 6. The temperature convergence at several interfaces

6. CONCLUSIONS

Domain decomposition method is applied successfully for the 3-dimensional simulation of the piston-cylinder system of a hermetic reciprocating compressor. The convergent result is obtained by 9 iterations. All thermodynamic properties and other parameters can be obtained at each location as well as their contours or profiles at a certain cross section area.

NOMENCLATURE

$A_{lin,i \to gs}$	contact area between the segment i of the cylinder liner and the gas inside the shell	(m^2)
$A_{lin,i \to p,j}$	contact area between the segment i of the cylinder liner and the segment j of the piston sealing surface	(m^2)
$\dot{Q}_{cy \to g}$	heat transfer from the cylinder to the gas	(W)
$\dot{Q}_{cy \to gs}$	heat transfer from the cylinder to the gas inside the shell	(W)
$\dot{Q}_{cy \to p}$	heat transfer from the cylinder to the piston	(W)
$\dot{Q}_{lin}$	heat transfer at the cylinder liner	(W)
$\dot{Q}_{lin,i}$	heat transfer at the segment i of the cylinder liner	(W)
$\dot{Q}_{p,i}$	heat transfer at the segment i of the piston sealing surface	(W)
$\dot{Q}_{p,i}$	liner temperature	(°C)
$T_{p,j}$	temperature of segment j of the piston sealing surface	(°C)
α	convection coefficient	(Wm^{-2}K^{-1})

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