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A Numerical Study of Convective Heat Transfer in the Compression Chambers of Scroll Compressors

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ABSTRACT

Convective heat transfer in the compression chambers of scroll compressors affects important quantities associated with the compression cycle, such as the volumetric efficiency and the discharge gas temperature. In spite of its relevance, heat transfer in scroll compressors has not been sufficiently studied mainly due to difficulties associated with its geometry. This paper presents a numerical model developed to predict the convective heat transfer in the compression chambers of scroll compressors, by applying the finite volume method to solve the conservation equations for mass, momentum and energy. An equation of state for real gas was also considered to complete the system of equations and relate pressure, temperature and density along the compression cycle. Due to the singular geometry of scroll compressors, an algorithm was developed to adapt the computational mesh throughout the simulation. The near wall region plays an important role on heat transfer and hence a low Reynolds turbulence model was adopted in the solution procedure. Results for convective heat transfer coefficient are compared with values returned by correlations commonly adopted in the literature.

1. INTRODUCTION

One of the most undesirable thermodynamic losses of compressors is caused by heating the refrigerant before and during the compression process. Along its admission into the compressor, refrigerant is heated as it gets into contact with hot parts of the compressor, as the electric motor, crankcase, and compressor housing. The heat dissipation in the electric motor and bearings are the main heat sources inside the compressor. The heat released by the refrigerant gas throughout its compression process and heat coming from discharge cover are other significant sources. Part of the heat is rejected to the outside environment through the compressor housing, whereas the remaining part ends up heating the gas admitted from the suction line. Figure 1 outlines the interactions between the sources and the heat paths in a typical low-pressure housing scroll compressor.

Suction gas heating negatively affects the compressor thermodynamic efficiency. The first effect is the reduction of volumetric efficiency due to the decrease of gas density, reducing the cooling capacity of the system. The second consequence is the reduction of isentropic efficiency brought about by the associate increase of specific work of compression.

Most simulation models for thermodynamic analyzes of scroll compressors adopt integral formulations. The accuracy of such models depends on the adequate description of the physical phenomena involved. In the specific case of convective heat transfer between gas and scroll walls, two aspects are important: the convective heat transfer coefficient and the temperature profile of the scrolls. However, there are few studies in the literature dedicated to a comprehensive analysis of the convective heat transfer process in scroll compressors, greatly due to the level of complexity imposed by the restricted space for measurement and the time scales involved. Among the few works one can cite the investigations of Sunder (1997), Ooi and Zhu (2004) and Jang and Jeong (2006).
For reciprocating compressors and internal combustion engines, several empirical correlations have been developed, though there is a large discrepancy between them. On the other hand, the experimental determination of heat transfer coefficients inside the scroll compressor pockets is a remarkable challenge, reflected in the lack of studies on the subject.

The present paper aims to provide a better understanding of the phenomenon of heat transfer inside the compression chambers of scroll compressors. For this purpose, use is made of a differential numerical model that considers the geometrical characteristics of the scroll wraps and transient effects throughout the gas compression process. Gas leakage is neglected and the analysis is limited to the suction and compression processes. Despite such simplifications, the differential numerical model developed is able to provide valuable information on the convective heat transfer during compression as well as during the suction process in which low temperature gas is admitted into the scroll pockets.

2. MATHEMATICAL MODEL

The convective heat transfer inside the compression chamber during the suction and compression processes is numerically analyzed taking into account the unsteady effects promoted by the motion of the orbiting scroll. The solution domain corresponds to the gas pocket formed during the suction process.

Due to the singular geometry of scroll compressors, an algorithm was developed to adapt the computational mesh throughout the simulation. The two-dimensional model here developed is similar to those presented by Pietrowicz et al. (2002) and Ooi e Zhu (2004), in which only one gas pocket is simulated. However, the model adopts a different approach for generating and updating the solution domain at each time step. Furthermore, the model was extended to allow the analysis of convective heat transfer between gas and scroll wraps also during the suction process.

The numerical model was developed with a commercial CFD code (ANSYS Fluent v.12.1.4) in which the governing equations of conservation of mass, momentum and energy are solved by the finite volume methodology. The real gas models provided in Refprop 8 (NIST, 2007) were used to complete the system of equations so as to relate pressure, temperature and density along the compression cycle. A second-order upwind scheme was adopted to interpolate the flow quantities needed at the control volume faces. The coupling between the pressure and velocity fields was achieved with the SIMPLEC scheme. The system of algebraic equations was solved with a segregated implicit algorithm.
The compressible turbulent flow that prevails in the compressor was solved through the concept of Reynolds-averaged quantities, in which the value of a computed variable represents an ensemble average over many cycles at a specified spatial location. The turbulence transport contribution was modeled through the Realizable $k-\varepsilon$ model. Moreover, the turbulent Prandtl number ($Pr_t$) is estimated via the correlation proposed by Kays and Crawford (1993), in which $Pr_t$ varies according to the turbulent viscosity ratio:

$$\frac{1}{Pr_t} = \left( 0.5882 + 0.228 \left( \frac{\mu}{\mu_t} \right) - 0.0441 \left( \frac{\mu}{\mu_t} \right)^2 \left[ 1 - \exp \left( \frac{-5.165}{\mu/\mu_t} \right) \right] \right)$$

The near wall region plays an important role on heat transfer and hence a low Reynolds turbulence model was adopted in the solution procedure. Due to the importance of the mesh refinement near the walls to allow the solution of the viscous sublayer, the mesh generation follows two criteria:

(i) the value of $y+$ in the cells adjacent to the walls was kept in the order of 1. Values of $y+$ greater than 1 are acceptable provided they are within the viscous sublayer ($y+ < 5$);

(ii) the viscous layer region ($y+ < 30; Re_y < 200$) was refined with at least 10 cells so as to properly estimate turbulence quantities.

Figure 2 illustrates the solution domain and the mesh refinement for a specific time step. The grid nodes are repositioned at each time step to update the chamber geometry, respecting the aforementioned grid requirements. The total number of nodes remains constant throughout the simulation.

Values for evaporating pressure and suction temperature were employed as boundary conditions for the suction chamber inlet during the suction process. Along the compression process there is no mass flow across boundaries. In other words, gas leakage is not taken into account. The simulation procedure employed time steps equivalent to crank angles with 1 degree resolution.

### 3. RESULTS AND DISCUSSIONS

The numerical results obtained with the differential model described before were compared to typical correlations for internal flows. In fact, the correlation of Dittus-Boelter, a correlation for spiral heat exchangers (hereafter denominated Spiral HEX correlation) and the correlation proposed by Jang and Jeong (2006) are commonly adopted in the modeling of scroll compressors. For convenience, these models are listed below in terms of the Nusselt number, $Nu$:
- Correlation of Dittus-Boelter:

\[
\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{n}
\]  

(2)

- Correlation for spiral heat-exchanger (Spiral HEX correlation):

\[
\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{n} \left(1 + 1.75 \frac{D_h}{R_c}\right)
\]  

(3)

- Correlation of Jang and Jeong (2006):

\[
\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{n} \left(1 + 1.75 \frac{D_h}{R_c}\right) \{1 + 8.48[1 - \exp(-5.35\text{St})]\}
\]  

(4)

In Equations (2)-(4), the exponent \(n\) assumes a value of 0.4 for gas heating and 0.33 for gas cooling. In order to estimate the convective heat transfer via these correlations, it is necessary to evaluate the Reynolds number, \(\text{Re}\), given by

\[
\text{Re} = \frac{\rho U_s D_h}{\mu}
\]  

(5)

which in turn is characterized by the gas velocity, \(U_s\), and the hydraulic diameter, \(D_h\), defined as:

\[
U_s = 2\pi a (2\pi N + \pi - \theta^*) f_e
\]  

(6)

and

\[
D_h = \frac{4V}{A_s}
\]  

(7)

where,

\[
\theta^* = \begin{cases} 
2\pi, & \theta < 2\pi \\
\theta, & \theta \geq 2\pi
\end{cases}
\]

(8)

It should be mentioned that when leakage is not considered, \(\text{Re}\) as defined by Eqs. (5)-(7) remains constant along the compression process. Finally, \(\text{St}\) is the Strouhal number, defined by Jang and Jeong (2006) as:

\[
\text{St} = \frac{f_e D_h / 2}{U_s}
\]

Figure 3 shows the average heat flux between the gas and the scroll wraps along the suction and compression processes for the geometry of a typical scroll compressor operating with R-22. The correct evaluation of the heat flux between gas and the scroll walls throughout the compression process requires a proper temperature profile for the scroll wraps. Unfortunately, such data was not available. For convenience, the wall temperature, \(T_w\), was then kept constant throughout the simulation, such as \(T_w = 15^\circ\text{C}\). Thus, the gas is heated during suction and along the initial stages of the compression processes.

As shown in Figure 3, the model proposed by Jang and Jeong (2006) predicts heat fluxes much higher than estimates from the other models. In fact, none of the evaluated models shows a close agreement with the differential model throughout the simulation. For the specific case of the compressor analyzed, the correlation of Dittus-Boelter provided results in closer agreement with predictions of the differential model. However, changes in the operating condition and/or scroll wrap geometry can significantly change such results.

Figures 4 and 5 present results of heat transfer coefficients (HTC) along the gas compression process for a compressor running at extreme operating conditions represented by the Reynolds numbers of \(10^5\) (LBP) and \(1.2 \times 10^5\) (HBP). For convenience, the results given by the correlation of Jang and Jeong (2006) are not presented because
they are much higher than the other results. At low Reynolds number, the correlations of Dittus-Boelter and Spiral HEX estimated lower HTC in comparison with the differential model (Figure 4). On the other hand, when \( Re = 1.2 \times 10^5 \) both correlations predict values for HTC higher than those returned by the differential model (Figure 5).

The results in Figures 4 and 5 also show that HTC predicted by the differential model increases with the orbiting angle, even though Re and Pr remain constants. This behavior is also verified with the Spiral HEX correlation and it is consequence of the increase of wrap curvature. On the other hand, the Dittus-Boelter correlation is only function of Re and Pr, and, as a consequence, estimates for HTC remain almost constant along the compression process. The small variation observed at the end of compression process occurs because the geometry of the scroll wraps is different at the central region (perfect-mesh profile).

![Figure 3: Results of heat flux along the suction and compression processes.](image)

![Figure 4: Variation of the heat transfer coefficient along the compression process; Re = 10^5.](image)
4. CONCLUSIONS

This paper presented a numerical model developed to predict convective heat transfer in the compression chambers of scroll compressors along the compression cycle. Due to the singular geometry of scroll compressors, an algorithm was developed to adapt the computational mesh throughout the simulation. Special attention was given to the near wall region due to its important role on heat transfer. Results for heat transfer coefficient were compared with values returned by correlations commonly adopted in the modeling of scroll compressors. None of such correlations was able to predict the convective heat fluxes throughout the suction and compression process in line with the differential model developed in the present study. The major deviations were noted at higher Reynolds numbers, typical of HBP applications.

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