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ABSTRACT

This paper presents the development and validation of a simulation model of an injection scroll compressor that can be used for optimization of a heat pump system for electric vehicles. The modeling considered the effects of refrigerant leakage and suction gas heating. The simulation model solved continuity and energy conservation equations using 4th Runge-Kutta scheme to predict the pressure and temperature variations according to scroll revolution. The refrigerant mass flow rate, compressor discharge temperature, and compressor power input were calculated. The results of the simulation model were validated with the experimental data. The simulation model predicted the compressor performance within ±10% deviation. The simulation results showed characteristics of injection process with the orbiting angle.

1. INTRODUCTION

Most of electric vehicles use the vapor compression cycle for the cooling and the PTC (positive temperature coefficient) heater for the heating. However, the use of the PTC heater can decrease a traveling distance of the electric vehicle due to the considerable battery consumption. Recently, a heat pump system has been considered as a heating system in the electric vehicles. Kim *et al*. (2012) compared the heating characteristics of a PTC heater and a heat pump for electric vehicles. Cho *et al*. (2013) conducted a study on the performance characteristics of a mobile heat pump for a large passenger electric vehicle. Even though the heat pump had a huge advantage in terms of energy efficiency, its heating performance reduced significantly because of automotive refrigerant R134a at low ambient temperatures. Therefore, it is possible to use a heat pump system for heating of the electric vehicles by applying the gas injection technique. In order to predict and optimize the system performance, it is necessary to analyze the performance of an injection compressor. The objective of this study is to develop and validate a simulation model for an injection scroll compressor in a heat pump for electric vehicles.

2. MODELING OF AN INJECTION SCROLL COMPRESSOR

A compressor was an asymmetric injection scroll compressor with 27 cc displacement volume for electric vehicles. The compressor model was divided into A pocket and B pocket, and each of the pockets composed of a suction chamber, compression chamber, discharge chamber, and an injection port. Thermodynamically analyzing a series of processes (suction, compression, discharge) with increasing a scroll orbiting angle, the compressor model calculated refrigerant properties to consider the injection process. The simulation model was developed by using Visual Basic 6.0, and the thermodynamic properties of the refrigerant were calculated by REFPROP 7.0.

2.1 Governing equations

The governing equations for the compressor modeling were derived from the continuity equation and energy conservation equation as a function of the scroll revolution, which are given in Eqs. (1)-(2). The temperature and pressure in the compression process could be solved by using these equations.

$$\frac{dm}{d\theta} = \frac{dm_i}{d\theta} - \frac{dm_o}{d\theta} + \frac{dm_{inj}}{d\theta} \tag{1}$$

$$\frac{dT}{d\theta} = \frac{\dfrac{1}{m}\left[\dfrac{dm_i}{d\theta}(h_i - h) + \dfrac{dm_{inj}}{d\theta}(h_{inj} - h) - \dfrac{dm_o}{d\theta}(h_o - h)\right] - \left[(\dfrac{\partial h}{\partial v})_T - (\dfrac{\partial P}{\partial v})_T v_c\right]\dfrac{dv}{d\theta}}{\left[(\dfrac{\partial h}{\partial T})_v - (\dfrac{\partial P}{\partial T})_v v_c\right]} \tag{2}$$

2.2 Mass flow rate

The refrigerant leakages inside the compressor through the clearances between a fixed scroll and orbiting scroll were calculated by Eqs. (3)-(4) (Park et al., 2002). This equation was one-dimensional compressible flow equation in a nozzle with an assumption of an isentropic process. The injection mass flow rate was also calculated by Eqs. (3)-(4).

$$\frac{dm}{dt} = C_{\mathrm{d}} A P_{\mathrm{up}} \sqrt{\frac{2k}{R(k-1)T_{\mathrm{up}}}\left[\left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right)^{2/k} - \left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right)^{(k+1)/k}\right]} \quad \text{for } \left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right) \geq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{3}$$

$$\frac{dm}{dt} = C_{\mathrm{d}} A P_{\mathrm{up}} \sqrt{\frac{2k}{RT_{\mathrm{up}}}\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \quad \text{for } \left(\frac{P_{\mathrm{down}}}{P_{\mathrm{up}}}\right) < \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{4}$$

2.3 Injection hole area

The uncovered area of the bypass holes (Liu et al., 2009) was used to calculate the area of injection hole. According to the equation, calculations for each condition are given as follows:

If $\mathrm{li} \geq t + r$, then the uncovered area is

$$A_{By} = \pi r^2 \tag{5}$$

If $\mathrm{li} \geq t$ and $\mathrm{li} \leq t + r$, then

$$A_{By} = \left\{\pi - \tan^{-1}\left[\frac{\left(r^2 - \mathrm{lo}^2\right)^{0.5}}{\mathrm{lo}}\right]\right\} r^2 + \mathrm{lo}\left(r^2 - \mathrm{lo}^2\right)^{0.5} \tag{6}$$

If $\text{li} < t$ and $\text{li} \geq t - r$, then

$$A_{By} = r^2 \tan^{-1}\left[\frac{\left(r^2 - \text{lo}^2\right)^{0.5}}{\text{lo}}\right] - \text{lo}\left(r^2 - \text{lo}^2\right)^{0.5} \tag{7}$$

If $\text{li} \leq t - r$, then

$$A_{By} = 0 \tag{8}$$

2.4 Model algorithm

Input values of the model included the geometry of the scroll compressor, the compressor speed, and the refrigerant properties by the suction and injection. With the orbiting angle increasing by $\Delta\theta$ from 0^o to θ_{end}, the calculation was performed for the suction / compression / discharge processes. Because the governing equations were first-order ordinary differential equations, all equations were solved with the fourth-order Runge-Kutta method according to scroll revolution at the infinitesimal time interval. The governing equations in the compression considered whether the injection operation worked or not. The entire process was repeated three times. The first iteration assumed that the suction gas heating and the refrigerant leakage were not taken into account. In the second, iteration the temperature rise of the suction gas was considered without the refrigerant leakage. The third iteration was based on both of the suction gas heating and the refrigerant leakage. After the iteration, the mass flow rate, power consumption, discharge properties were estimated.

2.5 Model validation

The compressor model was validated with using the measured data of an injection heat pump for electric vehicles. In this study, an asymmetric scroll compressor was used in the experiment and simulation. The compressor frequency could be increased up to 8000 rpm. The experiments were conducted with and without injection. The performance of the injection scroll compressor was measured by varying the compressor speed and outdoor temperature. The compressor speed and the outdoor temperature varied from 3600 rpm to 7200 rpm and from 7°C to -15°C, respectively. The results were compared with the experimental data at the same operating conditions. The mass flow rate and power consumption of the compressor were compared with the measured data. As shown in Figure 1, the mass flow rate and power consumption of compressor were compared with the measured data. The maximum deviations of the predicted mass flow rate and power consumption were 9.53% and 10.02%, respectively. The deviations of the compressor model were within 10% for approximately 95% of the experimental data.

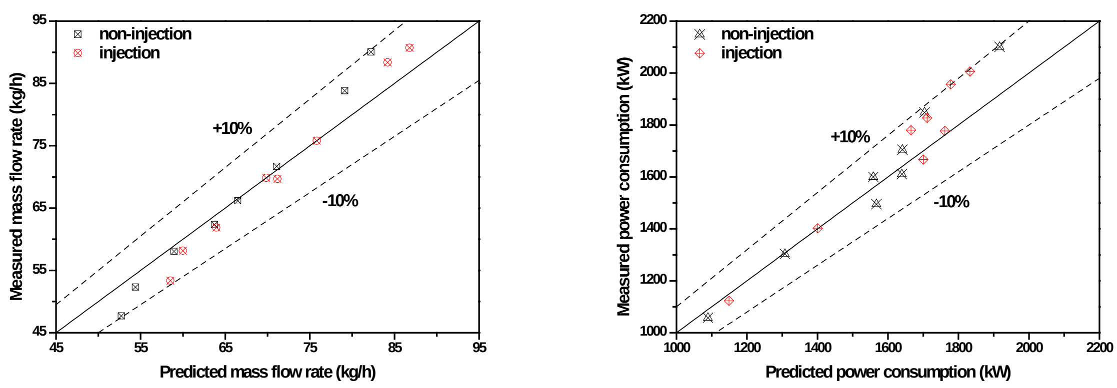

Figure 1: Deviations of the simulation model results

3. RESULTS AND DISCUSSION

The detailed process of simulation model was investigated with using calculation of the refrigerant properties as function of the orbiting angle. The temperature and pressure variation were shown in figure 2 from suction to discharge process. They were predicted using 4th Runge-Kutta method to solve the continuity and energy conservation equations. From figure 2, it could be seen that suction processes of A pocket and B pocket were within angle of 0-360^o and 0-540^o, respectively. The temperature and pressure of the refrigerant increased until the pressure reached the discharge pressure. Tendency of the temperature and pressure at the A pocket and B pocket was different because each pocket had different volume.

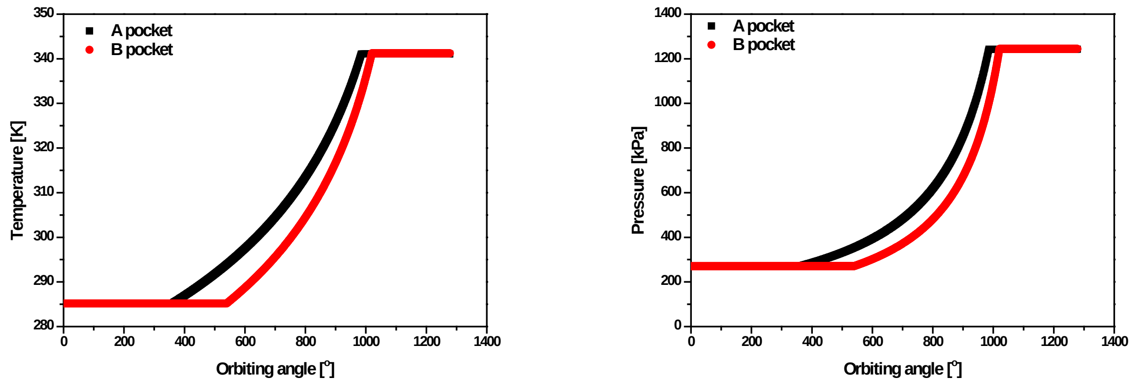

Figure 2: Variation of the pressure and temperature with the orbiting angle

In the injection scroll compressor, the injection starting point which was related with a location of the injection hole influenced on the injection mass flow rate and system performance. The compressor used in this study had an injection hole angle of 285^o. Figure 3 shows the variation of the injection mass flow rate with the orbiting angle for pockets A and B, respectively. The refrigerant injection of the A pocket started at the orbiting angle of 364^o with the injection period of 207^o. After the end of the A pocket injection, the refrigerant injected continuously into the B pocket with the injection period of 146^o. Because of asymmetric geometry, each of the pockets had the different injection period. With the injection after 360^o, the loss in the injection mass flow rate was not observed due to early injection before completion of the suction process. However, a slight loss was observed due to the late injection. Because the pressure difference between the compressor pocket and injection decreased, the late injection loss occurred. The B pocket showed more reduction in the late injection.

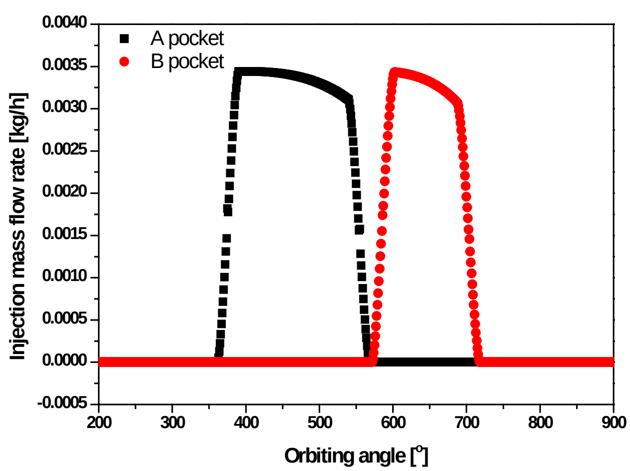

Figure 3: Variation of the injection mass flow rate with the orbiting angle

4. CONCLUSIONS

A simulation model of the injection scroll compressor in a heat pump for electric vehicles was developed. The compressor model was based on the thermodynamic governing equations and fourth-order Runge-Kutta method. The refrigerant leakage and the suction gas heating were applied to the compressor model. The injection hole area was calculated by the uncovered area of the bypass holes as a function of the orbiting angle. In the model validation, the simulation results were consistent with the experimental data. The injection characteristics with the orbiting angle were investigated.

NOMENCLATURE

A	area	(m^2)
A_{by}	uncovered cross-section area	(m^2)
C_d	coefficient of the flow rate	(–)
h	enthalpy	(kJ/kg)
k	specific heat ratio	(–)
li	distance between inner involute and bypass hole center	(m)
lo	distance between outer involute and bypass hole center	(m)
m	mass	(kg)
P	pressure	(kPa)
R	gas constant	
r	radius of bypass hole	(m)
T	temperature	(K)
t	time	(s)
v	specific volume	(m^3/kg)
θ	orbiting angle of the scroll	(^{o})

Subscript

down	downstream
i	inlet
inj	injection
o	outlet
up	upstream

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