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Convection heat transfer model and verification for the vacuum chamber during charge and discharge processes

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ABSTRACT

The change of temperature is obvious in the vacuum chamber during charge and discharge processes. The thermodynamic model needs to consider the convection heat transfer between air and wall in the vacuum chamber. It is the most important to get the expression of the convection heat transfer coefficient on studying the convection heat transfer model. In previous researches of the pressure chamber, the expression of the convection heat transfer coefficient was complicated and related to the Reynolds number which had no accordant calculation method. To solve these problems, an alternative approach is proposed, relating the heat transfer coefficient to the rate of change of pressure. Based on the thermodynamic model of the chamber and combined with temperature curve obtained by the stop method experiment, the convection heat transfer coefficient during charge and discharge processes in the vacuum chamber is calculated. Then, the simplified expression of the convection heat transfer coefficient by the least square method is identified. Compared with the simulated and measured pressure response curves of 0.2 L and 0.8 L vacuum chambers, the convection heat transfer model with the simplified expressions during charge and discharge processes in the vacuum chambers is proved to be effective.

1. Introduction

Vacuum systems with the vacuum chamber are widely applied, such as atmospheric pressure simulator system, the industrial conveying system and the double-level dynamic vacuum system [1–3]. The study of the pressure response of the vacuum chamber during charge and discharge processes is the key in these systems, however the transient heat transfer which occurs is not well understood, nor is it well modeled. This is due to complexities of transient velocity, developing flow conditions, variable property effects, and others.

Generalized models for no heat transfer and average heat transfer rates were often used and were usually developed based on specific experimental conditions [4–9]. The hypothesis that there was no convection heat transfer during the charge and discharge processes of the pneumatic cylinder in the pneumatic servo positioning system was proposed [4–6]. Because they considered the response time of the actuator was much faster than the thermal time of the convection heat transfer process, and the process was adiabatic. Moreover, the temperature in the cylinder was assumed to be equal with the ambient temperature. Oubib and Richard [7] proposed that the charge and discharge processes were isothermal when the rate of change of pressure in the chamber during the charge and discharge processes was very low. Combined with the previous two hypotheses in Refs. [4–7], the separating process was proposed [8,9]. The researchers have shown that the discharge process is slower than the charge process in the same chamber. So the discharge process and the charge process were respectively considered to be isothermal and adiabatic.

In fact, the temperature during the charge and discharge processes had a clear change [10]. The convection heat transfer process was compared with the adiabatic process, the isothermal process and the separating process by simulation [11]. Simulation studies showed that the convection heat transfer model had the best accuracy in pressure prediction. In order to better study the pressure response, the convection heat transfer was taken into account in some studies [12–16].

The research of convection heat transfer is mainly concerned that how to get the expression of the convection heat transfer coefficient. The convection heat transfer coefficient *h* was changeable in the chamber during charge and discharge processes. To simplify the problem, Yang [12] and Guo [13] treated the convection heat

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transfer coefficient as a constant which was equal to the average value of h in a certain period of time. Obviously, the average value of h was seriously affected by the human factor.

The convection heat transfer was divided into the forced-convection heat transfer, the free-convection heat transfer and the mixed-convection heat transfer, and the relation of h and the Nusselt number Nu was deduced [14], and expressed as:

$$h = \lambda Nu/x \tag{1}$$

where λ is the air thermal conductivity and x is the characteristic dimension. Nu is unknown. At present, the main research method is to obtain the fitting expression of Nu by similarity principle. Then, the expression of h can be obtained. The Nusselt number of the forced-convection heat transfer was considered to be dependent on the Reynolds number Re and Prandtl number Pr. The exponential function which was the simplest type of relation was given:

$$Nu = CRe^{m}Pr^{n} \tag{2}$$

where C, m, and n are constants to be determined from the experimental data, $Re = \rho ux/\mu$ and $Pr = c_p\mu/\lambda$. u is the velocity, ρ is the density, μ is the dynamic viscosity, and c_p is the constant pressure specific heat.

Yang [15] considered the discharge process in the isothermal chamber was the forced-convection heat transfer. By the experiment, the two fitting expressions of Nu in sonic flow and subsonic flow of the solenoid valve were respectively expressed as:

$$Nu = \begin{cases} \left(-3.797\varphi^2 + 7.023\varphi - 3.221\right)(Re\bullet q)^{0.90}Pr^{1/3}, & \text{for sonic flow} \\ \left(-9.246\varphi^2 + 17.372\varphi - 8.095\right)Re^{0.88}Pr^{1/3}, & \text{for subsonic flow} \end{cases} \tag{3}$$

where φ is the porosity, q is the air compression ratio and the average velocity of air in the isothermal chamber was treated as the velocity u.

Gao [16] evaluated the flow intensity in the pneumatic cylinder by CFD method. Numerical results showed that the charge process of high-pressure air in the pneumatic cylinder was the forced-convection heat transfer, but the discharge process in the pneumatic cylinder was the mixed-convection heat transfer. Gao quoted directly the expression of Nu in Ref. [14]. The expression of Nu during charge process and discharge process were respectively expressed as:

$$Nu = \begin{cases} 1.75(\mu_b/\mu_w)^{0.14}\left[Gz + 0.012\left(GzGr^{1/3}\right)^{4/3}\right]^{1/3}, & \text{for discharge process} \\ 0.0214\left(Re^{0.8} - 100\right)Pr^{0.3}, & \text{for charge process} \end{cases} \tag{4}$$

where μ_b evaluated at the bulk temperature and μ_w evaluated at the wall temperature are the dynamic viscosity, Grashof number $Gr = g\beta(T_w\text{-}T_\infty)\ x^3/v^2$ and the Graetz number $Gz = Re\cdot Pr\cdot D/L$. The velocity near the wall was treated as the velocity u.

The theoretical derivation in Ref. [14] was aimed at the pipe flow and the flow around the cylinder. In Refs. [15,16], the expressions of h were complicated and the velocity u had no accordant calculation method. The uncertainty of position of velocity led to the uncertainty of the simulating results in Ref. [16]. The goal of this paper is to develop the simplified expressions of h in the vacuum chamber during charge and discharge processes, and is to get an unambiguous calculation method. Firstly, the thermodynamic model of the vacuum chamber is derived. Then, the experiments of the flow characteristic of the solenoid and the stop method are conducted to calculate the convection heat transfer coefficient. The influence of the air leakage and response time of the solenoid valve on the measuring temperature is analyzed. The simplified expression of h is obtained by fitting the heat transfer coefficient and the rate of change of pressure. Finally, the simulated and experimental pressure curves of 0.2 L and 0.8 L chambers are given to evaluate the validity of the convection heat transfer model with the simplified expression of h.

2. Mathematic model

The experimental principle sketch of the vacuum charge and discharge system is shown in Fig. 1. The system consists of a vacuum pump (Edwards, nXDS15i), a constant volume chamber, two solenoid valves (Festo, MFH-2-M5) with the switching time 5 m, a computer (Advantech, IPC-610 L) with a control board (Advantech, PCI-1716), two pressure sensors (Setra, 270- RoHS), a temperature sensor (Chaoyu, CYWPICIN). The experimental process is composed of charge mode and discharge mode. In the charge mode, the solenoid valve 1 is closed, and the chamber is connected with the atmosphere through the solenoid valve 2. Due to the pressure difference between the atmosphere and the chamber, air flows into the chamber to increase pressure. While in the discharge mode, the solenoid valve 2 is closed, air inside the chamber is released by vacuum pump through the solenoid valve 1 and the pressure will decrease. The pressure inside the chamber is measured by pressure sensor 1. The outputs of the sensors are passed to the computer via a data acquisition and control board. The control inputs are generated within the computer and passed to the solenoid valves by using the D/O capability of the PCI-1716 board. The temperature sensor is used in the experiment of the stop method.

The charge and discharge processes are analyzed using a global energy balance applied to the air in the vacuum chamber. This method of analysis excludes any spatial variations in heat transfer, but does allow for the time dependence of the processes to be examined clearly. The energy balance can be expressed from the first law of thermodynamics, written for an opened system: