Numerical analysis of vacuum pressure variation in refrigeration system used for household refrigerators

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ABSTRACT

The refrigeration system in household refrigerators undergoes a vacuuming process to remove all air prior to refrigerant charging. Any subsequent increase in absolute pressure within the refrigeration system can lead to performance deterioration. This deterioration in performance is primarily due to the gas load effects from residual air, underscoring the need for accurate assessment of these impacts. One such gas load effect, termed virtual leakage, refers to the gradual release of air from internal clearances or trapped volumes within the system. Notably, the compressor—a key component in refrigeration system—has a complex structure with potential clearances or trapped volumes where virtual leakage may occur; however, investigations into this factor have been limited. In this research, a numerical analysis method was developed to evaluate the impact of virtual leakage within the compressor and was validated by comparing it with experimentally measured pressure changes. The results indicated that approximately 15% of the compressor's internal flow path volume consisted of trapped volumes.

KEY WORDS

Vacuum analysis, Gas load, Virtual leakage

1. INTRODUCTION

The residual air inside a refrigeration system acts as a representative non-condensable gas, hindering heat transfer within the heat exchanger, and leading to higher energy consumption[1]. Therefore, to avoid these problems, a vacuum process is performed to remove the air—specifically, the gas load—from inside the refrigeration system before refrigerant charging. Gas load refers to the effect of gas molecules present within the system on the internal gas pressure. Therefore, a vacuum pressure analysis that considers these gas loads is necessary for improving refrigeration systems. Recently, Gim and Jeong[2] proposed a vacuum pressure analysis model considering the impact of gas load during the vacuuming process in refrigeration systems; however, However, this model did not consider the effects of virtual leakage, one of the gas loads. As shown in Fig.1, virtual leakage refers to the gradual release of air from trapped volume within the system. The compressor, with its complex structure, is susceptible to the presence of clearances or trapped volumes, thereby requiring consideration of the effects of virtual leakage.

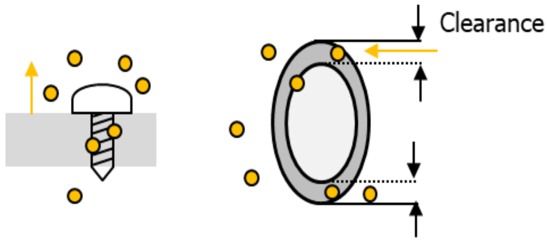

Fig.1: Example of virtual leakage.

2. MODELING

Fig.2 schematically illustrates the connection between the vacuum target system and the vacuum pump. As shown in the figure, during the vacuuming process, the influence of the vacuum pump generates gas flow within the system due to the pressure difference.

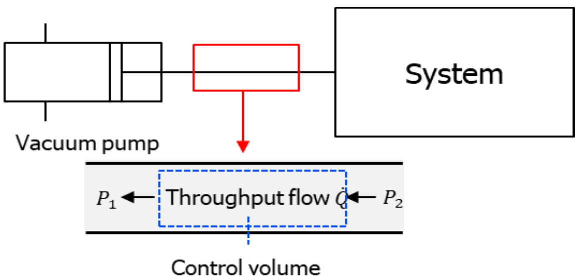

Fig.2: The throughput flow generated within the system.

The gas flow within the system is described using the concept of throughput flow ($\dot{Q}$), which is defined as the amount of gas transferred per unit time, as follows:

$$\dot{Q}_{sys}=\dot{Q}_{in}-\dot{Q}_{out}=V\frac{\Delta P}{\Delta t}=\Delta P\times\Gamma$$

Here, the term $\Delta P\times\Gamma$, represents the relationship between the pressure difference across the inlet and outlet within the system and the gas flow rate. Conductance (Γ), the inverse of flow resistance, indicates the ability of a component to permit gas flow. For a trapped volume (V_T), the air within this volume is released through a clearance with very low conductance(Γ_{path}). This release is due to the throughput ($\dot{Q}_{sys}$) caused by the pressure difference between the internal pressure of trapped volume(P_T) and the internal pressure of compressor (P_{comp}).

Since there is no incoming gas flow into the trapped volume ($\dot{Q}_{in}$=0), and the outgoing gas flow ($\dot{Q}_{out}$) is represented as the throughput flow ($\Gamma\Delta P$), the throughput flow equation for gas flow into and out of the trapped volume can be expressed as follows:

$$\dot{Q}_{sys} = -\dot{Q}_{out} = -\Gamma_{path}\left(P_T - P_{comp}\right) \quad (2)$$

If the time interval is very short, the pressure within the trapped volume, which has not yet been influenced by the pressure reduction in the compressor, remains unchanged. The throughput flow equation for the trapped volume, based on this assumption, is expressed as follows:

$$\dot{Q}_{sys} = -\dot{Q}_{out} = -\Gamma_{path}\left(P_T(i+1) - P_{comp}(i+1)\right) \quad (3)$$

Here, i represents the time variable. Before the vacuum pump operates, the internal pressure of the system is assumed to be equal to atmospheric pressure. By applying the ideal gas equation, the change in the number of molecules within the trapped volume can be expressed as follows:

Here, ΔN_T represents the change in the number of molecules within the trapped volume, k_B is the Boltzmann constant, and T is the air temperature.

$$\Delta N_T = \frac{\left(P_T(i+1) - P_T(i)\right)V_T}{k_B T} \quad (4)$$

Assuming that an increase of ΔN_T molecules increases the internal pressure of the compressor, the impact of virtual leakage on the system's internal pressure can be evaluated.

3. RESULTS AND DISCUSSION

Based on the methods outlined, a new vacuum pressure prediction model was developed, enhancing the model proposed by Gim and Jeong. Since it is practically impossible to account for all trapped volumes within a refrigeration system, this study considered only the trapped volume located inside the compressor. After the vacuum pump ceased operation, the analysis compared the compressor's internal pressure changes predicted by the vacuum pressure model with those measured experimentally. The results of this comparison are shown in Fig 3.

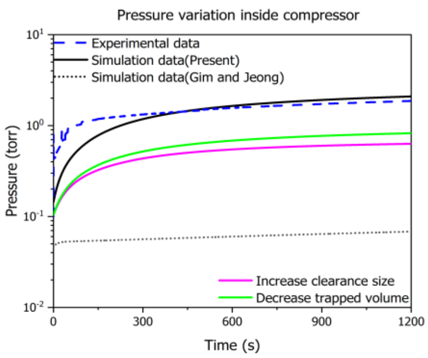

Fig.3: Comparison of experimental and simulation values.

Table 1: Additional explanation for Fig.3.

Line	V_T/V_{comp} [%]	Clearance size
Black*	15	5μm
Green	15	10μm
Pink	7.5	5μm

*Standard condition

Here, V_{comp} represents the volume of the refrigerant flow path inside the compressor. The size of the trapped volume is assumed to exist as a certain percentage of V_{comp}. The clearance size was determined using values that comply with the tolerance standards for precision sliding motion of mechanical components according to Japanese Industrial Standard (JIS) B0401[3,4]. Assuming that discrepancies between values predicted by the existing model and those measured experimentally are due to the exclusion of virtual leakage, the standard condition* closely followed observed trends. Compared to the standard condition*, increasing the clearance size enabled a smoother release of molecules from the trapped volume during vacuum pump operation, resulting in a diminished rate of pressure increase. Additionally, reducing the trapped volume size decreased the number of trapped molecules, which further contributed to a diminished rate of pressure increase.

4. CONCLUSION

In this research, a numerical analysis method was developed to evaluate the impact of virtual leakage within the compressor, and the results were compared with experimentally measured pressure changes. It was found that when air was released through a 5μm clearance from a trapped volume occupying 15% of the compressor's internal refrigerant flow path volume, the model closely followed observed trends. Additionally, increasing the clearance size or reducing the trapped volume size diminished rate of pressure increase in the vacuum pressure prediction model. This suggests the possibility of additional trapped volumes that need to be considered within the compressor.

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