Performance analysis of a suction muffler in a hermetic reciprocating compressor using CAA techniques based on Lattice Boltzmann Method

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ABSTRACT

A suction muffler in a hermetic reciprocating compressor is used for reducing noise induced by pressure pulsation inside the compression chamber. Since complex flow passages inside the suction muffler inevitably lead to the adverse effects on the efficiency of the compressor, high-performance mufflers in terms of both flow and acoustics are favored. However, the acoustic and flow performances of the muffler are still separately assessed in terms of the insertion loss and pressure drop in the related industry. In fact, flow and acoustic waves inside the muffler interacts strongly so that the separate prediction cannot provide the reliable assessment for each performance. In this paper, acoustic and flow performances of a suction muffler used in a reciprocating compressor is numerically investigated using the computational aeroacoustic (CAA) techniques based on the Lattice Boltzmann Method, which solves flow and acoustics simultaneously. To improve the accuracy of numerical simulation results, the measured static pressure at the inlet of the compression chamber is used at the outlet boundary condition. The energy conversion between the acoustic and vorticity waves are identified, which manifests that the interactions between the flow and acoustic quantities play important roles in determining the acoustic and flow performances of a muffler. The identified physical phenomena can be used to provide new design concepts to maximize the flow rate while keeping the noise level at a minimum.

Keywords: Muffler, Flow noise, Acoustic wave, Vorticity wave, Lattice Boltzmann Method
I-INCE Classification of Subjects Number(s): 51.4

1. INTRODUCTION

With rising living standards, the interest in environmental issues has increased. Along this trend, customers consider acoustic power of home appliance to be one of most important index to determine its performance. Compressors are important mechanical devices frequently used in home appliances and thus low noise design is important issue in developing compressors. A suction muffler in a hermetic reciprocating compressor is the typical device used for reducing noise induced by pressure pulsation inside the compression chamber in the compressor. However, complex flow passages inside the suction muffler inevitably lead to the adverse effects on the efficiency of the compressor. For this reason, the muffler should be developed considering its performances in terms of flow as well as acoustics. However, the acoustic and flow performances of the muffler are still separately assessed in the related industries. In fact, flow and acoustic waves inside the muffler interacts strongly so that the separate prediction cannot provide the reliable assessment for each performance. In this paper, acoustic and flow performances of a suction muffler used in a reciprocating compressor is numerically investigated using the computational aeroacoustic (CAA) techniques based

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on the Lattice Boltzmann Method, which solves flow and acoustics, simultaneously. Lattice Boltzmann Methods(1,2) based on the Boltzmann equation governing the distribution of gas molecules are reported to be successfully applied for predicting flow noise in internal flow problems similar to the current problem. First, to verify the validity and accuracy of the LBM in predicting acoustic performance of the target muffler, numerical result of transmission loss of the muffler without flow is compared with the FEM solution. Then, acoustic and flow performances of the suction muffler in a hermetic reciprocating compressor are investigated using the LBM. The LBM is numerically realized using the commercial software, Power FLOW (version: 5.0a).

2. NUMERICAL SETUP

2.1 Lattice Boltzmann Method

In this section, the LBM is briefly introduced. Lattice Boltzmann models are based on Boltzmann equation but simplify Boltzmann's original conceptual view by reducing the number of possible particle spatial positions and microscopic momenta from a continuum to just a handful and similarly by discretizing time into distinct steps(1). The Lattice Boltzmann equation with the BGK(3) collision model is defined as the Lattice BGK(LBGK) equation in the form:

$$f_i(\vec{r}+\vec{c}_i\Delta t, t+\Delta t) = f_i(\vec{r},t) - \frac{\left[f_i(\vec{r},t) - f_i^{eq}(\vec{r},t)\right]}{\tau} \qquad (1)$$

where $f_i(\vec{r},t)$ describes the probability that at a certain time t, a particle is positioned at $\vec{r}$. $f_i(\vec{r}+\vec{c}_i\Delta t, t+\Delta t) = f_i(\vec{r},t)$ is the streaming part and $\left[f_i(\vec{r},t) - f_i^{eq}(\vec{r},t)\right]/\tau$ is the collision step. The discrete velocity directions for the D3Q19 which is popular type for 3D lattice are shown in Fig. (1).

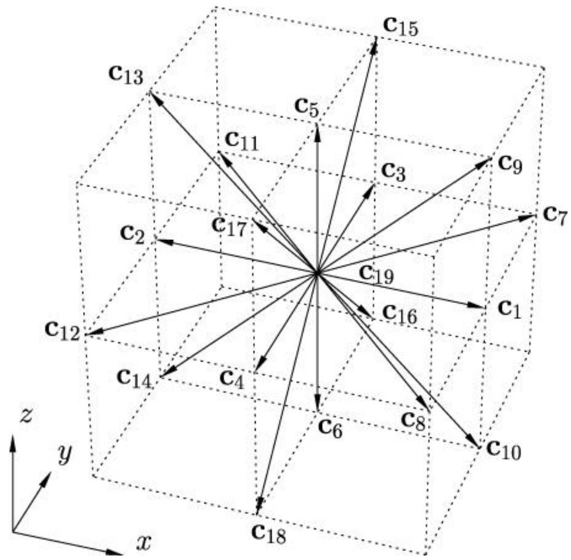

Figure 1 – The geometry of the D3Q19 lattice with lattice velocity vectors. (From Martin Hecht et al. (4))

The collision of the fluid particles is considered as a relaxation towards a local equilibrium distribution function f_i^{eq} (5) is defined as:

$$f_i^{eq}(\vec{r},t) = w_i\rho(\vec{r},t)\left[1 + 3\frac{\vec{c}_i\cdot\vec{u}}{c^2} + \frac{9}{2}\frac{(\vec{c}_i\cdot\vec{u})^2}{c^4} - \frac{3}{2}\frac{\vec{u}^2}{c^2}\right] \qquad (2)$$

where, ρ is density of fluid, w_i is lattice weights,

$$w_{1\sim6} = 2/36$$
$$w_{7\sim18} = 1/36 \quad (3)$$
$$w_{19} = 12/36$$

c_s is the sound of speed defined as $c_s = c/\sqrt{3}$ and kinematic viscosity is given by $\nu = c_s^2(\tau - \Delta t/2)$. The macroscopic density and velocity are defined as:

$$\rho = \sum_{i=1}^{19} f_i \quad (4)$$

$$\rho\vec{u} = \sum_{i=1}^{19} \vec{c}_i f_i \quad (5)$$

The LBM applied by BGK model falls into stream and collision operations. Then, particle distributions can be computed with appropriate boundary conditions.

2.2 Target Muffler and Details on LBM Simulation

Computational domain inside the target muffler and inlet fluid surrounding the inlet duct of the muffler are shown in Fig. 2. The applied boundary conditions (BCs) are summarized in Table 1.

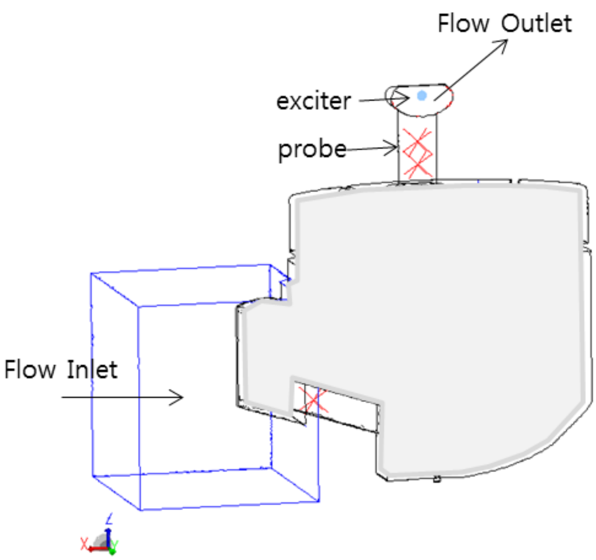

Figure 2 – Computational domain of suction muffler

Table 1 – Properties and boundary conditions (6)

Refrigerant	R600a
Density (Kg/m^3)	1.37
Characteristic temperature (K)	326.6
Wall temperature (K)	311.45
Flow inlet pressure (Bar)	0.624
Flow outlet pressure (Bar)	Time dependent

No-slip BC is applied on the wall of the suction muffler and the temperature on the wall boundaries are set to be 311.45(K). At the inlet boundary, the pressure and temperature are set to be constant values of evaporating pressure,0.624Bar and characteristic temperature, 326.6 K, respectively. At the outlet boundary (inlet to the compressor chamber), the prescribed time-varying pressure is applied when the inlet valve of the compressor chamber is opened, which is obtained from the measurement and the no-slip wall boundary condition is applied when the valve is closed.

3. Results and Analysis

3.1 Acoustic performance with flow

In this section, acoustic performance of the muffler without flow effects is computed using the LBM and the finite element method (FEM), respectively. The latter method is used for comparison with the LBM. The purpose of comparison between two methods is two-fold. First is to validate the LBM solver for acoustic computation and second is to assess the effects of viscosity on acoustic computation, which is generally neglected in typical acoustic solvers such as the FEM based on the frequency-domain solver for the wave equation. The FEM is numerically realized using the SYSNOISE. The TL is computed using the white noise at the acoustic inlet of the muffler in the LBM. The TL is calculated using the Three Point Method (7) for both simulations. Measuring points are shown in Figure 2. Figure 3 compares the transmission loss(TL) of the suction muffler predicted using the FEM and LBM. It is seen that two results are in good agreement. The reason for some discrepancy between two results seems to be the viscosity effects and the reflected waves off the acoustic outlet boundary in the simulation using the LBM. The exact reasons need to be made clear by further study.

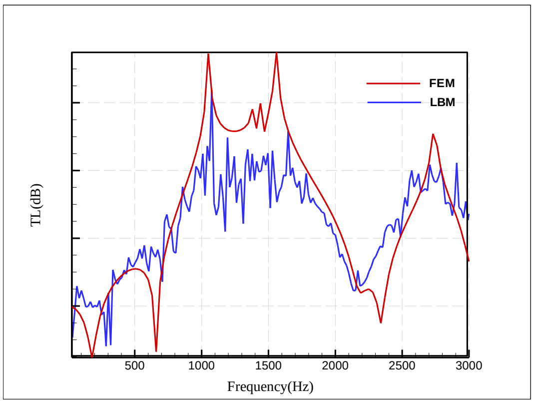

Figure 3 – Comparison of transmission loss between FEM and LBM

3.2 Performance with Flow Effects

In this section, performances of the muffler in terms of flow and acoustic are investigated including the flow effects.

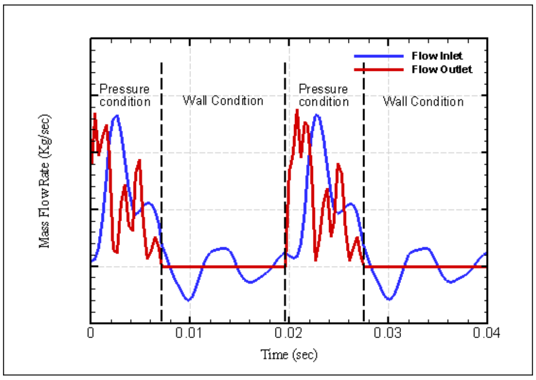

Figure 4 – Time-histories of mass flow rates computed at the inlet and outlet of flow

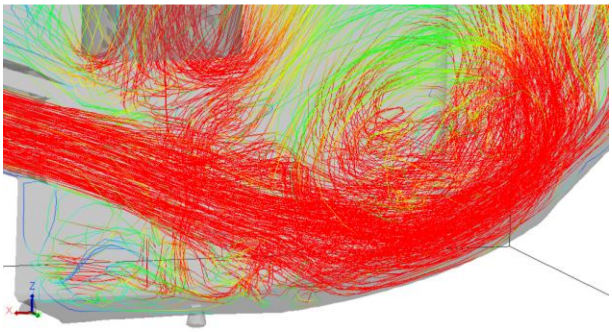

Figure 5 – Fluid stream lines with colored by velocity magnitude inside the main chamber of the muffler at 0.025097(sec)

Figure 4 shows the mass flow-rate computed at the flow inlet and outlet during 2 rotations of the crank in the compressor. The suction valve is opened at ‘pressure condition’ and closed at ‘wall condition’. Backflow is observed at the flow inlet during ‘wall condition’. This backflow seems to be associated with the propagation of pressure wave from the flow outlet when the suction valve is closed. Figure 5 shows the stream lines colored by their corresponding velocity magnitudes at the time t= 0.025097 sec. It is found that refrigerant hits the inner surface of the muffler after passing through inlet pipe strongly. This collision result in adverse effects on the performance of the muffler in terms of flow as well as noise.
The time-varying signals of static pressure computed near the flow inlet and outlet are shown in Fig. 6. The magnitudes of static pressure at the flow inlet are much lower than those at the flow outlet. For quantitative comparison, the transmission loss computed using these pressure data is computed and shown in Fig. 7 with the TL computed without flow shown in Fig. 3.

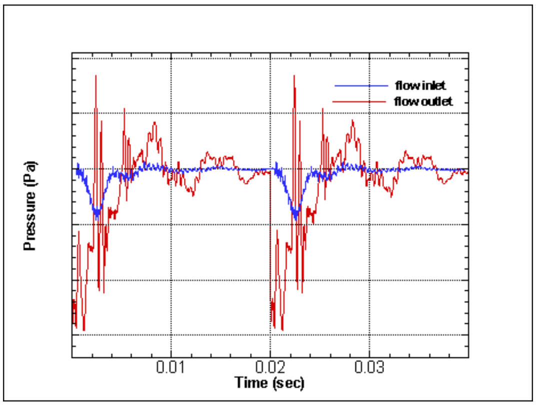

Figure 6 – Pressure at flow inlet and flow outlet

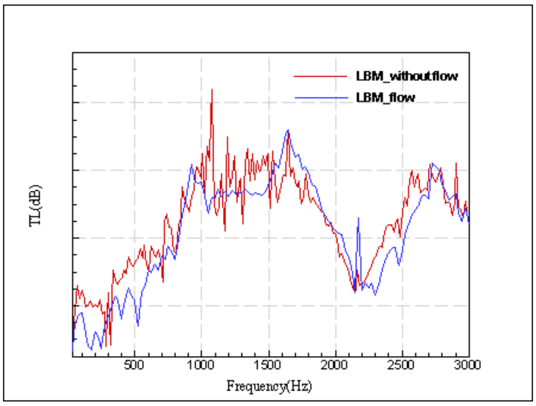

Figure 7 – Comparison of transmission loss between without flow and flow conditions

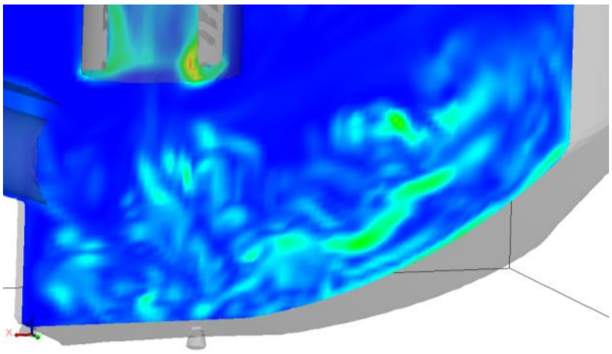

Figure 8 – Vorticity distributions inside main chamber of the muffler at 0.025097(sec)

Figure 8 shows the computed vorticity magnitudes in the suction muffler at the time t=0.025097(sec) when the suction valve is opened (pressure condition). It is seen that most of the vortices are formed inside the main duct pipe and near the wall where the strong collision by refrigerant leaving from the inlet pipe on the wall occurs, as shown in Fig. 6. Since these vorticity waves can be converted into acoustic waves, these waves can be considered as additional noise sources. These interactions between the vorticity and acoustic waves cannot be considered in the TL prediction without flow, shown in Fig. 3, which can explain the difference observed in Fig. 7. The performance of the muffler in terms of acoustic and flow can be improved by controlling these vorticity waves.

CONCLUSIONS

In this paper, flow and acoustic performances of the muffler are investigated using the CAA techniques based on the LBM. Reverse flows are observed when the inlet valve of the compressor room is closed, which leads to adverse effects on the performance of the muffler. The predicted TL of the muffler with flow effects shows some differences with the TL computed without low effects. This difference originates from the complex interactions between the vorticity and acoustic waves inside the muffler. The high-performance muffler in terms of both flow and acoustic can be developed by developing new designs to control generation of these vorticity waves. These results illustrate the merits of the present approaches to solve the flow and acoustic waves simultaneously over the typical methods based on separate computations for acoustic and flow.

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