Aeroacoustic noise from fans contributes significantly to the overall noise emissions from heat pumps. The noise emitted from the fan is affected by the characteristics of the flow on the suction side, which may vary depending on the type of heat exchanger and the distance between the heat exchanger and the fan. To investigate these effects, experimental studies have been conducted using a model of a heat pump outdoor unit with an adjustable casing. Acoustic measurements were performed with two different heat exchanger models: one with classical round tubes and fins and another with microchannels. It was found that the round tube heat exchanger produces larger tonal components in the sound power spectra than the microchannel heat exchanger. The results also show that the levels of the tonal components become larger as the distance between the heat exchanger and the fan increases. The scenarios were also modelled numerically in OpenFOAM®. Experimental and numerical results exhibit similar tendencies with respect to the flow characteristics. Reproducing the spectral characteristics of the noise emissions for different heat exchanger types and relative heat exchanger - fan placements in numerical simulations remains a challenge and is subject of ongoing research. 

Keywords: (Aeroacoustics, heat pump, OpenFOAM)

1. Introduction

The anthropogenic climate change due to the wasteful usage of fossil fuels is one of the central challenges of the 21st century. In order to assume responsibility for future generations, efficient and environment-friendly heating systems can significantly reduce primary energy consumption. In this context, heat pumps have been identified as a key technology, especially heat pumps using outside air as a heat source. In recent years, the number of heat pumps installed in dense urban areas has been increasing continuously. Hence, the noise emission from heat pumps is becoming a serious issue. Therefore, acoustic research on heat pumps has become a major challenge in the development process of heat pump manufacturers. In the »WAMS« research project, the acoustic emission of heat pumps is investigated. A big topic in this project is the aeroacoustic noise from fans which contributes significantly to the overall noise emissions from heat pumps. The noise emitted from the fan is affected by the characteristics of the flow on the suction side, which may vary depending on the type of Heat Exchanger (HEX) and the distance between the HEX and the fan. In the present paper, an experimental setup is presented which is similar to a heat pump outdoor unit. This setup is used to investigate a typical HEX-fan combination as usually used in heat pump outdoor units. The investigations are carried out with two different heat exchanger models: a round tube (RT)-HEX and a microchannel (MC)-HEX. To date, RT-HEX are used in almost all stationary heat pumps. MC-HEX are currently mostly used in mobile application. However since MC-HEX offer similar or higher thermal efficiency with less refrigerant charge, there are many ongoing
investigations regarding their potential usage in air-water heat pumps [1]. In addition, a simulation model has been created, which closely represents the experimental setups. Preliminary aeroacoustic simulations have been performed in the open source software OpenFOAM®. Considering a simplified fan geometry, the estimation and characterization of the heat pump acoustic emissions were conducted using transient simulations and the acoustic analogy by Ffowcs Williams and Hawkings described in [2]. The sound pressure spectra are estimated at probe points on the pressure side of the heat pump model. The initial simulation results show that the applied open source acoustic library, might be a promising tool to estimate the aeroacoustic source characteristics of the rotating fan.

In Section 2 the laboratory heat pump mock-up and experimental setups are described. In Section 3 the experimental results are presented and discussed. Finally the aeroacoustic modelling is described and the results from initial simulations are presented.

2. Heat pump mock-up and experimental setup

Figure 1 shows the mock-up used for the investigations on the effects of the HEX-fan interaction. The mock-up has been designed and constructed at the Fraunhofer ISE, where it was used for heat transfer experiments [1]. At the Fraunhofer IBP it has been used for acoustic experiments and flow analysis. The mock-up is similar to a general heat pump outdoor unit in which the HEX and the fan are installed in series. The casing is made from plywood plates, with carefully sealed edges to avoid unintentional in-flow. The mock-up has an adjustable frame which allows to move the HEX relative to the fan.

![Figure 1: a) Picture of the heat pump mock-up in the semi-anechoic room; b) sectional drawing of the mock-up.](image)

The experiments were performed in a semi anechoic room (Figure 1a). The operating points, i.e. the rotational speed of the fan, is controlled via MODBUS connection. In the experimental studies two HEX-types, a RT-HEX with plain fins and a MC-HEX (see Figure 2a) with different pressure losses (see Figure 2b) are used. Three HEX-fan distances (10 cm, 20 cm, 40 cm) and four rotational speeds (40 %, 60 %, 90 %, 100 %), relative to the maximum fan rotational speed $\omega_{\text{max}} = 1060 \text{ rpm}$, have been considered.

![Figure 2: RT-HEX and the MC-HEX; a) Appearance and geometry and b) pressure losses.](image)
The sound power has been determined experimentally according to the reverberation room method described in DIN EN ISO 3741 [3]. Figure 3a shows the heat pump mock-up placed in a reverberation room. The sound pressures in the diffuse field were measured at six locations using half inch microphones. The 180° radiation characteristics on the pressure side of the heat-pump mock-up have been investigated in the semi anechoic room (Figure 1a). Figure 3b shows the top view of the 19 microphone positions used for measuring the sound radiation characteristics in the semi anechoic room. Measurements were conducted in three horizontal planes; one on the centre line of the fan and the other two ± 0.5 m above and below. For brevity, in this paper only results for the centre plane are presented.

![Figure 3: Measurement setups; a) heat pump mock-up in the reverberation room and b) sketch of the microphone positions for measurements of the sound radiation characteristics in the semi anechoic room.](image)

### 3. Experimental results

This section presents the measured results for the radiated sound powers and the radiation characteristics. The effects of the HEX-fan distance on the sound emissions are first discussed with respect to the results measured with the RT-HEX. Then the results for the MC-HEX are presented and discussed in direct comparison to the results from the RT-HEX. The fan has been controlled with respect to the fan speed, hence the fan speeds were independent of the other configurations of the experimental setup. Table 1 gives the **Blade Passing Frequencies (BPFs)** for the selected fan operation conditions.

<table>
<thead>
<tr>
<th>Fan rotation speed/rpm.</th>
<th>423 (40 %)</th>
<th>635 (60 %)</th>
<th>954 (90 %)</th>
<th>1060 (100 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade passing frequency/Hz</td>
<td>49.4</td>
<td>74.1</td>
<td>111.3</td>
<td>123.7</td>
</tr>
</tbody>
</table>

The A-weighted sound power levels for the measurements with RT-HEX are summarised in Table 1. For all fan speeds the measured sound power levels decrease with increasing HEX-fan distance. However, for constant fan speeds the overall sound power levels do not change much with the HEX-fan distance. A maximum level difference of ΔLWA =1.5 dB between LWA(10cm) and LWA(40cm) is measured for a fan speed of 423 rpm. As expected, the fan speed has a significant influence on the measured sound power levels. A maximum level difference of ΔLWA =25.8 dB between 40 % and 100 % fan speed is measured for the HEX-fan distance of 40 cm.

<table>
<thead>
<tr>
<th>Rotation speed/rpm.</th>
<th>LWA(10cm)/dB(A)</th>
<th>LWA(20cm)/dB(A)</th>
<th>LWA(40cm)/dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>423 (40 %)</td>
<td>54.2</td>
<td>53.1</td>
<td>52.7</td>
</tr>
<tr>
<td>635 (60 %)</td>
<td>64.4</td>
<td>63.9</td>
<td>64.2</td>
</tr>
<tr>
<td>954 (90 %)</td>
<td>75.4</td>
<td>74.9</td>
<td>75.7</td>
</tr>
<tr>
<td>1060 (100 %)</td>
<td>78.6</td>
<td>78.3</td>
<td>78.5</td>
</tr>
</tbody>
</table>
The 1/3 octave band sound power spectra for the measurements with the RT-HEX are shown in Figure 4. At low frequencies the sound power spectra are dominated by peaks around the BPF and its higher harmonics. The peak around the BPF is visible in all spectra, except in that for the fan speed setting of 40 %, since the BPF for this setting falls below the lower end of the investigated frequency range. For all fan speed settings, except for the 90 % setting, the 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonics of the BPF are clearly visible, even in the 1/3 octave band spectra. The peaks around the BPF and its harmonics stand out more clearly with increasing HEX-fan distance and are most pronounced for a HEX-fan distance of 40 cm. For fan speed settings of 60 % and 90 % the difference in the levels in the 100 Hz 1/3 octave band for 40 cm and 10 cm HEX-fan distance is about 6.3 and 9.6 dB, respectively. In contrast, for a fan speed setting of 100 % there is almost no difference in sound power levels around the BPF depending on the HEX-fan distances.

The broad band component of the sound powers increase steadily with frequency up to about 1 kHz. Above 1 kHz the sound powers decrease with increasing frequencies. For fan speed settings of 90 % and 100 % the levels drop at a rate of about 2 dB per octave and show almost no dependency on the HEX-fan distance. The spectra for the fan speed settings of 20 % and 40 % show similar shapes. However, for decreasing HEX-fan distances, the levels at higher frequencies are increasing.

Hence, it is interesting to note, that by choosing smaller HEX-fan distances it may be possible to reduce the magnitude of tonal peaks around BPF and its harmonics. However, the overall sound power level is dominated by the broad band noise components which have a maximum around 1 kHz. For higher fan speed settings this means almost no changes in the overall sound power levels depending on the HEX-fan distance. For lower fan speed setting, reducing the HEX-fan distance may cause an increase in the A-weighted overall sound power level. However, the effect of the HEX-fan distance on the tonal noise components should be further investigated from a sound perception point of view.

![Figure 4](image-url)
Both, the RT-HEX and the MC-HEX give relatively similar results. Table 3 gives the A-weighted overall sound power levels measured for the MC-HEX. The comparison of the results with the MC-HEX to those measured with the RT-HEX in Table 2, shows that the HEX design only has a small influence on the overall sound power level. The largest difference between sound power levels of the RT-HEX and the MC-HEX of $\Delta L_{W} = 1.1$ dB was measured for fan speed setting of 954 rpm and 40 cm distance.

Table 3: Sound power levels for different measurement setups with MC-HEX.

<table>
<thead>
<tr>
<th>Rotation speed/rpm.</th>
<th>$L_{WA}(10\text{cm})$/dB(A)</th>
<th>$L_{WA}(20\text{cm})$/dB(A)</th>
<th>$L_{WA}(40\text{cm})$/dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>423 (40 %)</td>
<td>53.3</td>
<td>52.2</td>
<td>52.2</td>
</tr>
<tr>
<td>635 (60 %)</td>
<td>63.8</td>
<td>63.1</td>
<td>63.4</td>
</tr>
<tr>
<td>954 (90 %)</td>
<td>74.8</td>
<td>74.3</td>
<td>74.6</td>
</tr>
<tr>
<td>1060 (100 %)</td>
<td>77.8</td>
<td>77.5</td>
<td>77.5</td>
</tr>
</tbody>
</table>

For direct comparison, the sound power spectra for both HEX types are plotted in Figure 5. In all measurements with the MC-HEX, for all fan speeds and a HEX-fan distance of 40 cm, the tonal peaks around the BPF and its harmonics is less pronounced than in the measurements with the RT-HEX. The maximum difference of 2.5 dB occurs in the 100 Hz 1/3 octave band for a fan speed setting of 954 rpm. Hence from an acoustic point of view, using a MC-HEX may offers additional potential for the reduction of tonal components.

Figure 5: Sound power spectra measured with RT-HEX and MC-HEX for different fan speed settings.
Figure 5 shows the results of radiated, A-weighted overall sound pressure levels, measured on the pressure side of the heat pump mock-up in the semi-anechoic room (see Figure 1a and Figure 3b) with a fan speed setting 60% (635 rpm, BPF = 74.1 Hz). Figure 6a shows the results measured with the RT-HEX for HEX-fan distances of 10 cm and 40 cm. The levels do not vary much from each other with the HEX-fan distance, which is in agreement with the measured sound power spectra shown in Figure 5. The maximum level of 69.1 dB(A) for the 40 cm HEX-fan distance occurs at an angle of 100°. The maximum level of 68.5 dB(A) for the 10 cm HEX-fan distance occurs at an angle of 100° as well. In general, the pressure differences between the 40 cm and 10 cm HEX-fan distance vary between 0.1 dB at 180° and 1.2 dB at 100°. Figure 6b shows the results measured with the RT-HEX and the MC-HEX, both for a HEX-fan distance of 40 cm. The maximum level of 67.2 dB(A) with the MC-HEX occurs at an angle of 100°. Depending on the angels, the pressure differences between the RT-HEX and the MC-HEX vary between 0 dB at 180° and 0.9 dB at 100°. In general, all results show a club-shaped radiation characteristic on the pressure side of the heat pump. Additionally, both radiation characteristics measured with the RT-HEX have two small climbs of the pressure level at 80° and 100°. Future studies will include the 360° radiation characteristics including the suction side of the heat pump mock-up.

Figure 6: Radiation characteristics for a) different HEX-fan distances b) for RT-HEX and MC-HEX.

4. Numerical Simulations

Supplementary numerical simulations have been conducted in order to gain a better insight into the aerodynamic and aeroacoustic mechanisms. All simulations were performed in OpenFOAM® v2006, using the incompressible transient flow solver pimpleFoam. The time step was set to Δt = 1e-5 s. In order to reduce computational effort, a simplified rotating fan model is used. The surface meshing was done in Salome and the 3D meshing was done using blockMesh and snappyHexMesh. Hence, a hexahedral-dominant mesh was generated with about 1.5 million cells and a maximum cell size of Δelement = 3 cm. The heat pump model is shown in Figure 7a. The geometry in brown represent the heat pump casing and the region in red represents the HEX, which is modelled as porous media. For simulating the fan rotation, a cylinder surrounding the fan (in blue) was defined and the Arbitrary Mesh Interface (AMI) was applied on the cylinder surface. The velocity dependent pressure losses gained in the experimental study (see Figure 2b) were taken to define the pressure losses in the porous media, modelled with the Darcy Forchheimer law (Eq. (1)) [4]:

\[ \nabla_i p = -\mu A_i u_i - \frac{1}{2} \rho B u_i^2, \]

where \( \nabla_i p \) represents the inertial pressure loss, \( \mu \) and \( \rho \) the dynamic viscosity, respectively the density of the ambient air. A and B are constants, determined by pressure measurements. The transient flow was simulated for \( \Delta t_{sim} = 2 \) s. For the estimation of the sound pressure data within \( \Delta t_{SP} = [1 \text{ s}; 2 \text{ s}] \) was used. The boundary conditions were selected to resemble the conditions as in the experimental setup. Hence,
ambient condition at the lateral boundaries, inlet condition on the suction side, and free outflow conditions on the pressure side were applied. In previous investigations [4], acoustic simulations were performed with the SNGR model which delivered insufficient results. Thus, in the current simulations the Ffowcs Williams and Hawkings (FWH) method described in [2] is used for estimating the sound pressure. Figure 7b shows the flow domain with the contour of the control surface for the FWH method (white line). The black dots indicate the probe positions at which the estimated sound pressures were analysed. The probe position have the same distance from the fan as in the experiments.

Figure 7: Heat pump model; a) geometry with porous media b) flow domain with probe locations.

Figure 8 shows simulated A-weighed sound pressure spectra for a fan speed of 1020 rpm., resulting in a BPF of 119 Hz. The spectra clearly show the peaks around the BPF and its higher harmonics. With an increasing angle from the mid axis, the sound pressure levels tend to decrease, which agrees with the findings in the experimental studies. To investigate the turbulence in the wake of the HEX, incompressible transient flow simulations with different flow velocities have been performed, using the pisoFoam solver. The transient flow was simulated for $\Delta t_{\text{sim}} = 2$ s with a time step of $\Delta t = 1e-4$ s. In order to reduce computational effort, only a small section was used for the flow analysis (Figure 9a). In this study, a hexahedral-dominant mesh was generated with about 4 million cells and a maximum cell size of $\Delta_{\text{element}} = 0.7$ mm. The boundary conditions were selected to resemble those in the experimental setup. Hence, symmetric condition on the lateral boundaries, an inlet condition on the suction side and a fixed velocity $v_x = [2 \text{ m/s}; 3 \text{ m/s}]$ on the outlet side, were applied. Figure 9b shows the visualisation of the turbulence analysis in the wake flow behind the HEX geometry. The isosurface of the vorticity magnitude $|\omega| = 600$ is plotted and coloured by the magnitude of the flow velocity $|v_x|$ in x-direction. The results show a change of the turbulent field with increasing distance from the HEX and for different velocities on the suction side. Hence, a change of these flow parameters may have an influence on the acoustic emissions of the fan. In the near future it is planned to conduct LDA measurements on the heat pump mock-up in order to validate the simulations against experimental results.

Figure 8: Simulated sound pressure spectra using the FWH method.
5. Conclusion

This paper presents results from experimental studies on the sound emissions and radiation characteristics of heat pumps using a mock-up with exchangeable HEX and adjustable HEX-fan distances. Two types of HEX have been considered, a classical RT-HEX and a MC-HEX. For fixed fan speeds there is little influence of the HEX type and the HEX-fan distance on the overall A-weighted sound power levels. However the 1/3 octave band spectra show that reducing the HEX-fan distance it may be possible to reduce the magnitude of tonal peaks around BPF and its harmonics. Furthermore, using a MC-HEX may offer additional potential for the reduction of tonal components. Hence the effect of the HEX-fan distance and HEX type on the tonal noise components should be further investigated from a sound perception point of view. With respect to the radiation characteristics, all setups investigated show a club-shaped radiation characteristic on the pressure side of the mock-up, without any significant irregularities. Future studies will include the entire 360° radiation characteristics including the suction side. The setups were also modelled numerically in OpenFOAM®. The simulations exhibit similar tendencies as the experimental results and seem to have potential to provide better insight into the aerodynamic and aeroacoustic mechanisms involved. However, the aerodynamic and aeroacoustic modeling of heat pumps remains a challenge. In order to validate the numerical simulations against experimental results, LDA measurements on the heat pump mock-up are planned for the near future.

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References


