DOI: 10.61782/fa.2023.0788

forum acusticum 2023

IMPACT OF HEAT EXCHANGERS ON AXIAL FAN ROTOR NOISE IN HEAT PUMP APPLICATIONS

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ABSTRACT

Due to installation effects, heat exchangers can increase the sound radiation of axial fans in heat pump applications. The increase in rotor noise is due to the disturbed flow field induced by the heat exchanger. In particular, the diameter of the coolant tube and the geometry of the heat exchanger have a major influence on the resulting sound radiation of the axial fan. Inhomogeneities in the flow field caused by the geometry of the heat exchanger housing have a significant influence on the tonal components in the fan's sound pressure spectrum. As the turbulence level increases, the broadband sound radiation of the fan increases due to the amplification of the leading edge sound sources. The tonalities in the radiated sound field and the total sound pressure level could be reduced in the future by appropriate selection of the heat exchanger parameters. This will allow the installation of quieter heat pumps in residential areas and thus increase the acceptance of the units by the public.

Keywords: *heat pumps, heat exchanger, rotor noise, axial fans, distrubed inflow*

1. INTRODUCTION

In recent years, weather extremes and new local heat records have become more frequent [1]. This is due to climate change. The resulting dry phases and heat waves mean that there is an increasing need for cooling in buildings. Ultimately, more air conditioning systems are being installed in private households and public buildings [2, 3]. Also based on climate change, besides the need for air conditioning, the demand for heat pumps is increasing year by year. Heat pumps are seen as a future-oriented technology to ensure the heating of buildings without fossil fuels. Thus, the increased demand for heat pumps is due to the political goal of climate neutrality and decentralized heating of buildings, to reduce greenhouse gases [4]. Both air conditioners and heat pumps are similar in principle and are based on a thermodynamic cycle. In the case of air conditioning, energy is extracted from a room and released into the environment outside the building. In the case of the heat pump, part of the energy required to heat the building is taken from the environment outside the building and then supplied to the rooms inside the building via a coolant fluid. In both systems, part of the required energy must be supplied in the form of electrical energy to drive the installed components. Fans and compressors can be identified as consumers, which should ideally be operated with electrical energy from renewable energy sources. However, it is precisely these components that bring with them a problem that reduces the acceptance of air conditioning systems and heat pumps. This is the generated sound radiation. As rotating machines, the built-in fans and compressors represent dominant flow-acoustic sound sources [5]. The radiated sound is usually perceived as disturbing or annoying by people who are in the vicinity of these systems. The increased background noise caused by these systems can make it more difficult for people to concentrate or can cause sleep or cardiovascular problems [6]. As the number of these systems continues to rise in the coming years, this problem will become even more relevant. There are already regulations from the govern-

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ment that heat pumps must be set to operate at low level at night in order to reduce noise in inhabited areas. Thus, the unwanted sound emission of the built-in compressors and fans not only promotes a possible rejection of the peoples towards these systems, but also presents the manufacturers with the challenge to reduce the sound emission more and more. With regard to the built-in fans, which are often axial fans because a high volume flow is required, several methods have already been developed to reduce the sound radiation of the fans. For example, forward skew of the fan blades has been identified as an effective way to extend the operating range and reduce sound radiation at the design point [7, 8]. Structural modifications to the fan blades, such as serrations [9], slits [10], porous materials [11], or winglets [12], also emerged as options for providing reduced sound radiation in future installations. However, in addition to optimizing the fan alone, as the main source of flow-acoustic sound, engineers still face the problem of installation effects as an additional challenge in the field of heat pumps and air conditioners. Installation effects are defined as aerodynamic and aeroacoustic effects on fans generated by additional internals and their interaction with the fan [13]. In the field of heat pumps, for example, this is the heat exchanger, which is usually positioned on the suction side [14]. The heat exchanger on the suction side can lead to a further increase in the sound radiation of the fans and to the fact that previously defined sound reduction measures no longer function. Both are due to the disturbed flow field induced by the heat exchanger interacting with the fan blades. Heat exchangers usually generate highly inhomogeneous flow fields, which exhibit increased turbulence levels [15]. These flow fields are much more difficult to integrate into optimization processes and are not specifically mappable in the aeroacoustic axial fan development process due to the large number of different heat exchangers. This paper focuses on the installation effects exerted by heat exchangers on axial fans in heat pump systems. Understanding the physical mechanisms that cause the rotor noise of fans to be increased by the flow field of heat exchangers is essential to derive generally applicable design specifications for heat pumps and air conditioners in the future to minimize sound radiation. In a first step, a sensitivity analysis of individual heat exchanger components is addressed. Based on these, the rotor noise of a forward-swept axial fan is discussed under the influence of various real heat exchangers. Finally, the findings regarding installation effects and their influence on the rotor noise of axial fans are summarized.

2. SENSIBILITY ANALYSIS OF HEAT EXCHANGER COMPONENTS

If a heat exchanger is located on the suction side of an axial fan, then individual components of the heat exchanger interact with the flow field. This interaction leads to disturbed inflow conditions for the axial fan [16]. The disturbed inflow conditions can lead to increased sound radiation from the axial fan. However, it is not clear which of the respective installed components has the greatest influence on the change in sound radiation. An investigation of this is confronted with the challenge that individual heat exchanger components must be changed independently of one another in order to be able to investigate the effects on the sound radiation separately from one another. Heat exchangers represent components with high costs and a high production effort, which can be justified by the high number of coolant tubes and cooling fins. Manufacturers have certain production guidelines which do not allow all parameters of the heat exchanger to be changed independently. In this sensitivity study, the parameters of coolant tube arrangement in and across the flow direction, coolant tube diameter, fin spacing, fin shape, housing geometry, and the shape of the transition between the heat exchanger and axial fan were investigated. For this purpose, more than 20 different heat exchangers were integrated into the test series and investigated with an industrial five-bladed forward-swept axial fan with a diameter of $D = 500$ mm. Figure 1 shows the results of the heat exchanger sensitivity analysis. It can be seen that the coolant tube arrangement, or the coolant tube radius, which are directly coupled to each other in the models used, as well as the heat exchanger geometry exert the greatest influence on the sound radiation of the axial fan. Due to their obstruction, the coolant tubes represent obstacles in the flow field, which can generate increased turbulence and e.g. Karman vortex streets. Therefore, it seems conclusive that these exert the greatest influence on the sound radiation of the axial fan. The fins, on the other hand, dampen turbulence due to their fine structures and the associated proximity of the flow to rigid walls. For this reason, they have only a minor influence on the sound radiation of the axial fan. In addition to the coolant tubes, the geometry of the heat exchanger plays a significant role in sound radiation. The geometry of the heat exchanger determines the global structure of the flow field to the axial fan and can therefore be the cause of inhomogeneous flow fields.

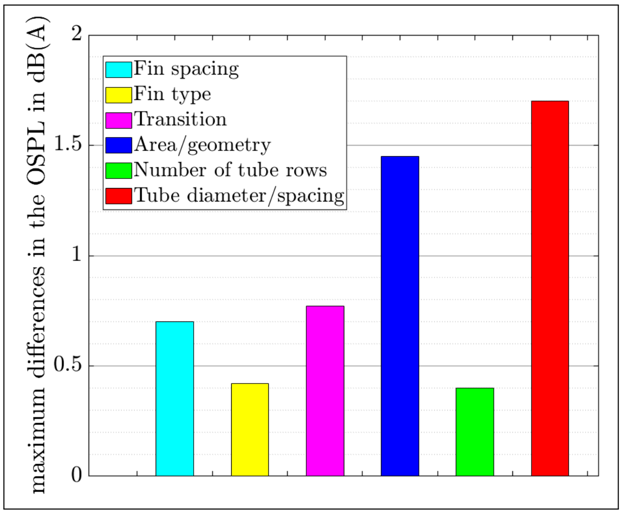

Figure 1. Sensitivity analysis of various heat exchanger components and their effect on the A-weighted overall sound pressure level (OSPL) of an axial fan. Shown are the maximum differences in overall sound pressure level that occur when only one parameter is changed at a time.

3. INFLUENCE OF THE COOLANT TUBE DIAMETER

The influence of the coolant tube diameter is to be analyzed again specifically on an integral and spectral level. For this purpose, a forward-swept axial fan with 9 blades and a diameter of 500 mm with two different suction-side heat exchangers is investigated. The investigations were carried out at the axial fan test rig of the LSTM Erlangen [?]. The heat exchangers differ only in the coolant tube diameter (9.52 mm and 12 mm diameter). Figure 3 and Fig. 2 shows the aerodynamic and aeroacoustic characteristics of the two variants and in addition the fan characteristics in the case of free flow. In the case of free inflow, no suction-side heat exchanger is installed upstream of the fan.

Increasing the coolant tube diameter increases the flow resistance of the heat exchanger and decreases the aerodynamic characteristics of the system (see Fig. 3). The overall sound pressure level increases due to the larger tube diameter. Differences of 2 dB can be observed between the two variants. One reason for this is the increased global turbulence level due to the two heat exchangers. For the small coolant tube diameter (9.52 mm),

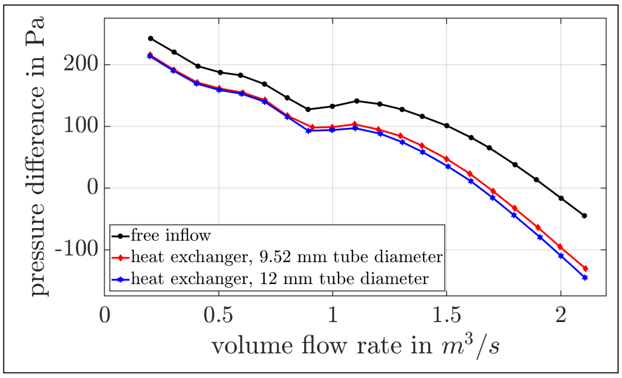

Figure 2. Aerodynamic characteristic curves.

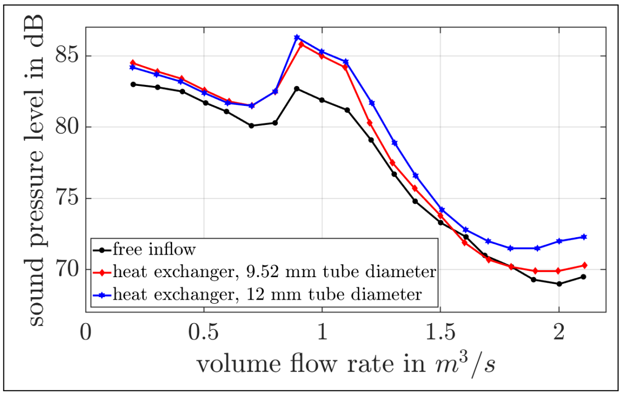

Figure 3. Aeroacoustic characteristic curves.

the average turbulence level is 6.73%. The larger tube diameter increases this to 8.12%. As described in [17], knowing the average spatial turbulence level is not sufficient to draw conclusions about sound radiation from the flow data. Therefore, Fig. 4 and Fig. 5 shows the spatial distributions of the turbulence levels of the two variants obtained from the 3D hot-wire measurements. The global increase of the turbulence level is clearly visible. There are also inhomogeneous turbulence spots due to the shape of the heat exchangers.

For the spatial variance of the turbulence level (see [17]) between the two variants, values of $4.56\%^2$ (9.52 mm coolant tube diameter) and $6.43\%^2$ (12 mm coolant tube diameter) are obtained. Higher values of this parameter indicate a more inhomogeneous flow field. Figure 6 shows the sound pressure spectra of the axial fan for the volume flow of $\dot{V} = 1.4m^3/s$ (fan design point). It can be seen that the increased sound radiation is mainly due to a broadband increase at low frequencies. This region can be

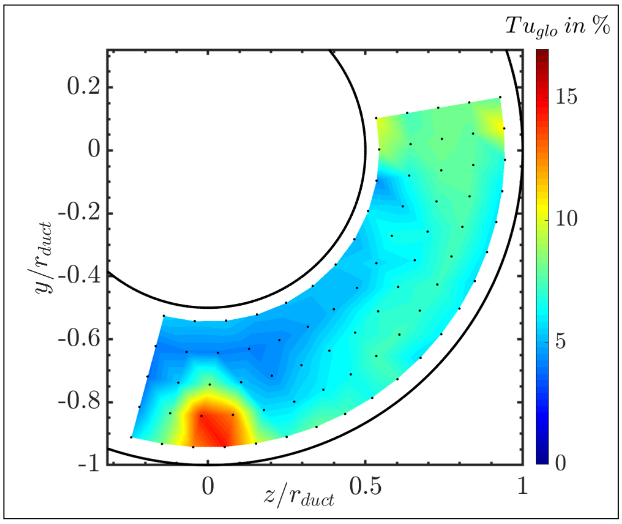

Figure 4. Turbulence level behind the heat exchanger with coolant tube diameter of 9.52 mm.

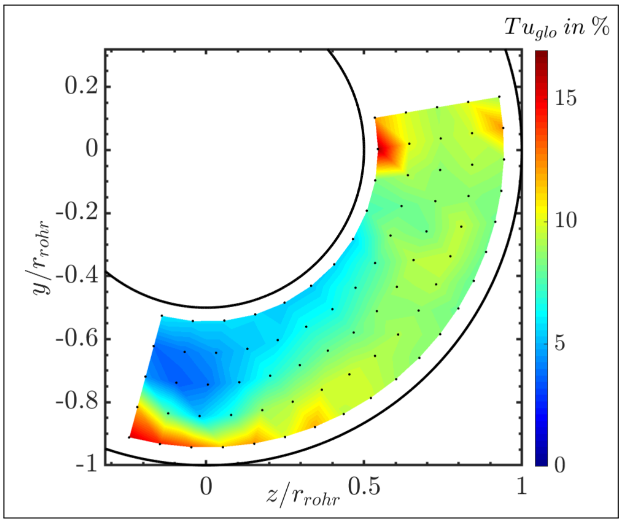

Figure 5. Turbulence level behind the heat exchanger with coolant tube diameter of 12 mm.

attributed to the leading edge of the axial fan, indicating a direct relationship to the disturbed inflows caused by the heat exchangers [18].

Simulations of entire heat exchangers with axial fans are currently not possible due to the need for very high spatial resolution and large domains. However, simulations of small heat exchanger segments can provide insight into the fluid mechanical conditions [19]. Figure 7 shows a variation of the coolant tube diameter based on numerical RANS simulations. This shows a clear increase in the downstream turbulence level as a function of the coolant tube diameter. Figure 8 plots the turbulence level downstream of the heat exchanger segment as a function of the coolant tube radius. It can be observed from both the experimental and numerical studies that the coolant tube radius increases the turbulence level of the inflow field to the axial fan and thus increases its broadband sound radiation in the low frequency range. Therefore, it can be recommended that small coolant tube radii in the suction side heat exchanger are desirable for low sound radiation from the axial fan. However, this design requirement must be balanced with thermodynamic conditions and manufacturing costs.

4. INFLUENCE OF THE HEAT EXCHANGER GEOMETRY

The geometry of the heat exchanger is dictated by the housing, which has the function of guiding the flow and protecting the coolant tubes and fins of the heat exchanger from damage. The geometry of the heat exchanger can usually only be varied between square and rectangular geometries. In this study, the geometry of a heat exchanger is varied between square, rectangular, and circular geometries by using geometric inserts. The inserts reduce the area of the heat exchanger, but keep the flow area identical between the geometries, which allows for a fair comparison. As a result, the pressure drop of the three variants is identical [15]. Figure 9 shows the aeroacoustic characteristics of a forward skewed axial fan (9 blades, 500 mm diameter) for the three different heat exchanger variants.

The circular geometry of the heat exchanger has the lowest sound pressure level. An analysis of the sound pressure spectrum shows that the differences are mainly due to the increased sound radiation at the blade passing frequency (223 Hz) of the fan. Here, a round geometry can significantly reduce the tonal peaks (see Fig. 10).

The reduction at the blade passing frequency compared to the square geometry is 11.2 dB for the operating point shown.

The reason for the difference in the tonal components of the sound pressure spectrum can be found in the flow field of the different variants, which was analyzed using 3D hot-wire anemometry. The angular housing shapes induce local turbulence spots due to the discontinuous transition from the angular heat exchanger housing to the round inlet nozzle of the axial fan. These are character-

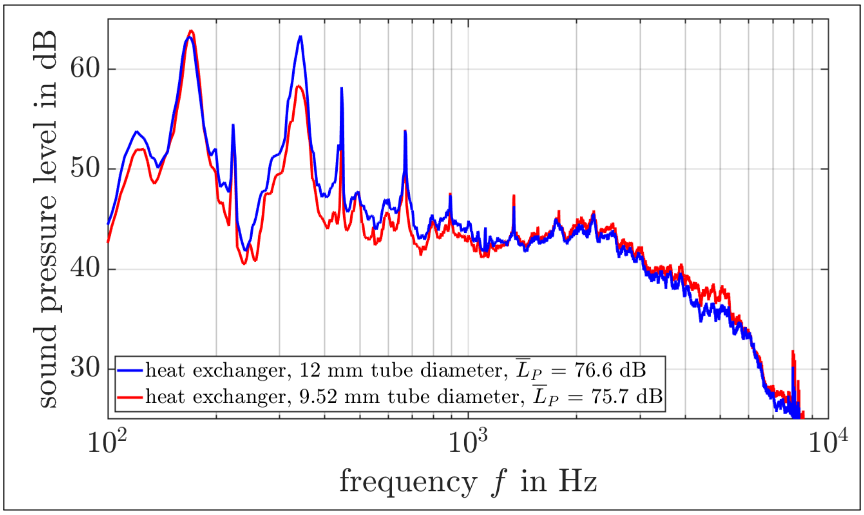

Figure 6. Sound pressure spectrum of the forward-skewed axial fan with two different heat exchangers on the suction side (difference in tube diameter only) at design volume flow rate ($\dot{V} = 1.4 m^3/s$) and design speed ($n = 1486$ rpm).

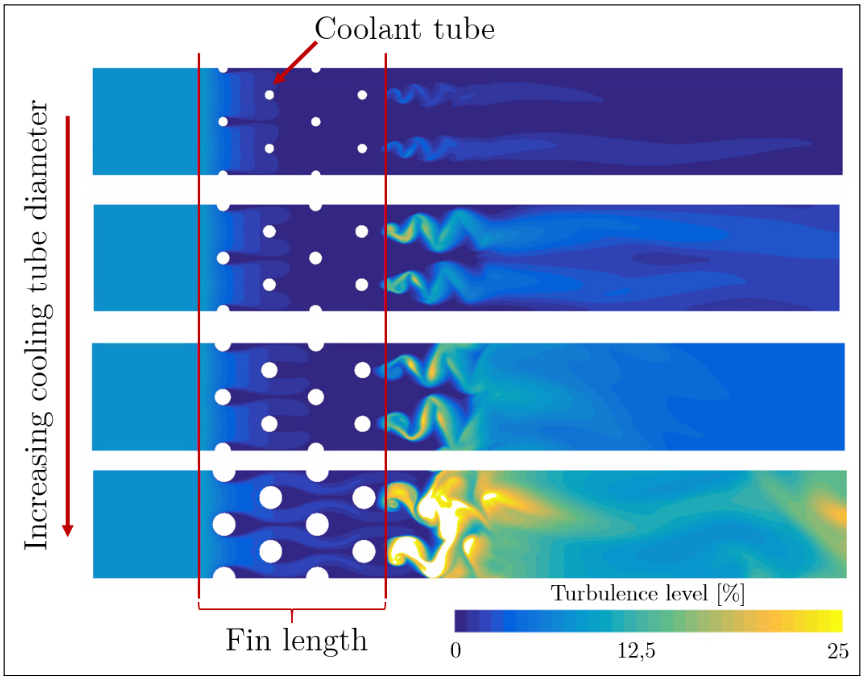

Figure 7. Turbulence level in different heat exchanger sub-segments, with periodic boundary conditions. Only the coolant tube diameter alone is increased from top to bottom.

ized by locally increased turbulence levels and increase the inhomogeneity of the flow field. The round geometry avoids this discontinuous transition and the turbulence level is spatially more homogeneously distributed in the

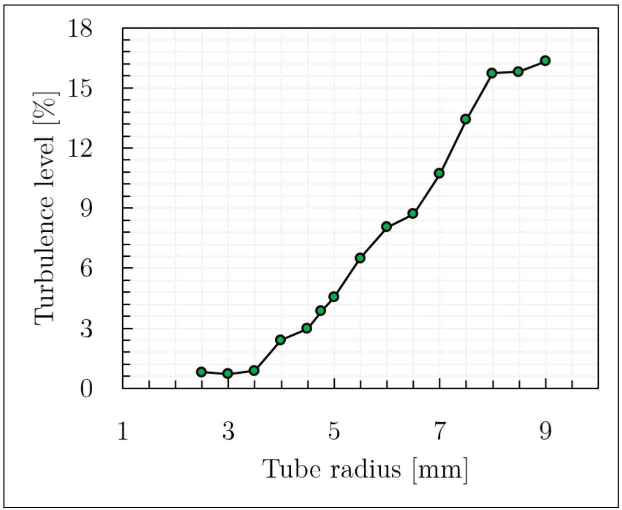

Figure 8. Numerical analysis of the influence of the coolant tube radius of heat exchangers on the induced turbulence level in the flow field downstream of the heat exchanger.

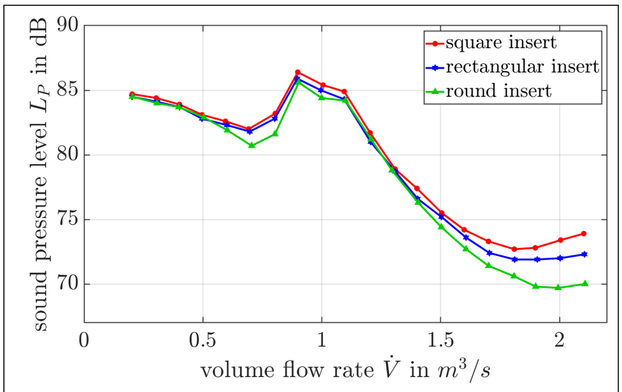

Figure 9. Aeroacoustic characteristic curves of the forward-skewed axial fan with installed suction-side heat exchangers, which differ in their housing geometry.

flow field. This is confirmed by the spatial variance of the turbulence level. The spatial variance of the turbulence level takes values of 22.3%^{2} for the square geometry, 21.6%^{2} for the rectangular geometry and 10.8%^{2} for the round geometry. The selected parameter thus confirms that a more homogeneous flow field can be generated by a round heat exchanger geometry. Inhomogeneous flow fields cause the blades to experience different loads per fan revolution depending on their location. These location-dependent variations in the angle of attack result in increased sound radiation at the fan blade passing frequency. As a result, the tonality increases and the noise of the heat pump becomes more unpleasant [20]. Based on the investigations, it can be concluded that the flow field should be as homogeneous as possible in order to reduce the tonal sound radiation of the fan. In the case of heat pumps, this can be achieved, for example, by a round geometry of the heat exchanger.

4.1 Conclusion

On the basis of an extensive sensitivity analysis, it was determined that the installation effects of heat exchangers on the sound radiation of axial fans are mainly determined by the coolant tube diameter and the geometry of the heat exchanger. Numerical and experimental investigations of the coolant tube diameter showed that the turbulence level in the flow field increases with increasing diameter. This leads to higher pressure fluctuations at the leading edge of the axial fan, resulting in a broadband low frequency sound amplification. The geometry of the heat exchanger is responsible for an inhomogeneous flow field. The localized turbulence spots increase the sound radiation at the tonal components (blade passing frequency) of the axial fan. From an acoustic point of view, it is recommended to use a small coolant tube diameter and a round heat exchanger geometry. These parameters result in lower sound radiation from the axial fan, but must be weighed against the thermodynamic requirements and manufacturing costs of the heat exchanger.

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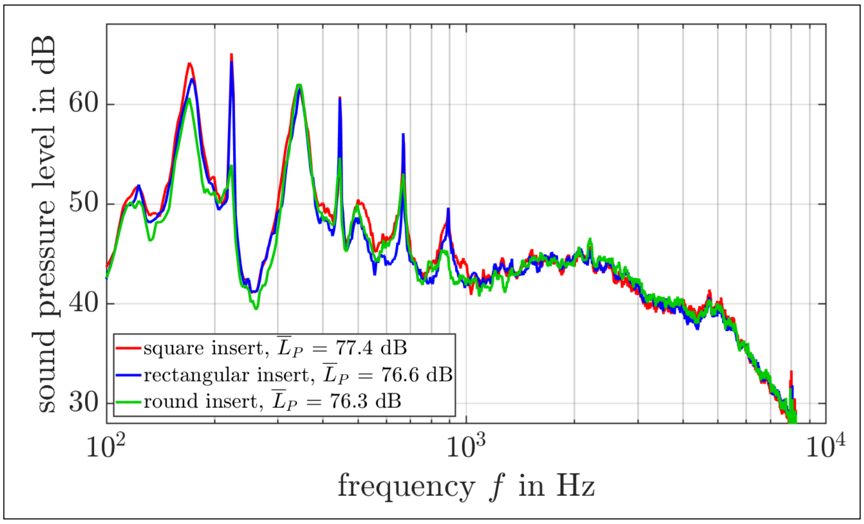

Figure 10. Sound pressure spectrum of the forward-skewed axial fan with three different heat exchangers on the suction side (difference in housing geometry) at design volume flow rate ($\dot{V} = 1.4 m^3/s$) and design speed ($n = 1486$ rpm).

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