PAPER ID: 0388
DOI: 10.18462/iir.compr.2021.0388

INFLUENCE OF REFRIGERANT AND COMPRESSOR CONSTRUCTION FORMS ON EFFICIENCIES ASSESSED BY DYNAMIC SIMULATION MODELS

Christian Vering, Christian Schwenzer, Stephan Göbel, Valerius Venzik, Markus Nürenberg, Dirk Müller

Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University
Aachen, 52074, Germany, cvering@eonerc.rwth-aachen.de

ABSTRACT

The compressor's performance is crucial for an efficient heat pump operation. In order to compare different refrigerants thermodynamically, efficiencies are often assumed constant and the influence of the construction form is neglected. The resulting steady-state comparisons allow first system insights without conducting expensive experiments. In dynamic operation, however, efficiencies vary due to compressor's rotational speed and its pressure ratio. This leads to different insights compared to previous steady-state results.

We present an open-source one-dimensional physical compressor model for a rolling piston-type and a reciprocating piston-type compressor in Modelica. It calculates both isentropic and volumetric efficiency depending on the refrigerant, construction form and operating point. Analysing all results, we prove our modelling approach to be valid. In conclusion, we apply the model to better understand the compression process in heat pump applications. Furthermore, regarding the design, different mechanical adjustments can be tested in the simulation model to estimate their performance impact.

Keywords: rotary piston compressor, thermodynamic modelling, efficiency comparison, compressor design

1. INTRODUCTION

In view of climate change progression, the European Union has set the goal of reducing carbon dioxide equivalent emissions by 80 % by 2050. The intention is to prevent the average global temperature from rising more than 2 °C until 2100. One promising approach to contribute to this issue is to reduce the overall primary energy consumption. In Germany, up to 25 % of the primary energy is used in the building sector to meet hot water and space heating demands. At present, most of this heat is generated by fossil fuel combustion which can be saved by using alternative, climate-friendly technologies. (European Commission, 2018), (Umweltbundesamt, 2018)

The heat pump represents a resource-saving alternative compared to the conventional gas boiler. A large part of the carbon dioxide emissions produced by electrically operated heat pumps is due to the use of electricity. However, as the share of renewable energy sources in the electricity generation mix is constantly growing, greenhouse gas emissions from heat pumps are continuously reduced. Compression heat pumps consist of four main components: (1) condenser, (2) expansion valve, (3) evaporator and (4) compressor. The compressor is driven by an electric motor, which accounts for a considerable share of the electricity consumption in the overall heat pump system. In order to exploit energy saving potentials in refrigerant circuits, it is, therefore, necessary to systematically investigate and improve the compression process. Both the refrigerant and the compressor construction form play important roles in this field of research. Both must meet political and technological requirements. On the one hand, a low environmental impact must be ensured. On the other hand, a high Coefficient of Performance (*COP*) of the heat pump must be achieved, which depends largely on high compressor efficiency. (Kelly, 2016), (Eifler, 2009)

For the characterisation of the compressor efficiency, the isentropic and the volumetric efficiency are typical parameters. The isentropic efficiency is a measure for the energy dissipation losses of the compression process. The volumetric efficiency evaluates the compressor in terms of mass flow. It describes the relationship between actual mass flow and theoretically maximum possible mass flow through the compressor. Both parameters are strongly fluid-dependent. (Roskosch, 2017), (Venzik, 2017)

In the early design stage of heat pump systems, the choice of working fluid and compressor combination plays a major role, because it defines the heat pump's temperature and pressure levels. Principally many different working fluids and compressor types exist. In order to improve the whole pre-selection and further design process, the efficient use of simulative methods for pre-selection gains in importance. For a reliable potential estimation, the thermodynamic states of the compressor inlet and outlet must be determined. In literature, there are already many theoretical studies which assume constant efficiencies for a simplified estimation (Cimmino, 2017), (Navarro, 2007), (Navarro-Peris, 2013). However, those simplifications can lead to a misguided selection (Venzik, 2017). First studies also use detailed models (Roskosch, 2017). However, a modular and scalable application for comparing different compressor types has not yet been developed.

Detailed heat pump simulation models are developed at the Institute of Energy Efficient Buildings and Indoor Climate (EBC). Currently, a reciprocating compressor model exists, which combines the geometric relationships between piston and cylinder with the thermodynamic compression process (Roskosch, 2017), (Göbel, 2021). To the best of the Authors, different compression phenomena regarding the compressor design have not been investigated on a physical level at EBC or other research facilities, yet. Furthermore, rolling piston compressors are increasingly used for heat pumps in the building sector. Therefore, in the context of this paper a rolling piston type compressor model is implemented in the modelling language Modelica. The refrigerant compression is then simulated with respect to varying boundary conditions.

According to an open-source simulation framework in (Vering, 2020), the model is based on a modular and scalable approach to ensure easy adaptation to shape, working fluid and heat transfer phenomena. Simulations are used to determine the compressor discharge (outlet) state, that is necessary for the calculation and evaluation of the isentropic and the volumetric efficiency as functions of the fluid and the states, respectively. For the comparison with reciprocating piston compressors, the model presented in Göbel et al. (Göbel, 2021) is used. The aim of the investigation is to create a refrigerant-dependent evaluation basis for compressors using the isentropic and volumetric efficiency in Modelica. Hence, the following article contributes to the model-based prediction of fluid-dependent performance of compressors and compares the construction form of a reciprocating piston compressor with a rolling piston compressor:

- Chapter 2: Introduction of the fundamental compression physics. In addition, the current State of the Art for modelling the rotary piston compressor are presented. Subsequently, the operating behaviour of a rolling piston compressor is examined and the compressor characteristics are presented.

- Chapter 3: Both compressor types are evaluated based on isentropic and volumetric efficiencies for operation in a heat pump with different alternative refrigerants as functions of pressure ratio and rotational speed.

- Chapter 4: A Summary of the results and an outlook for further research and the potential for improvement in the investigation of compressor design is given.

2. MODELLING APPROACH

In this Chapter, we present the State of the Art of different compressor modelling approaches. Accordingly, we compare and discuss the two common compressor constructions forms in Chapter 2.1: rolling piston-type (A, presented here) and reciprocating piston-type (B, presented in (Göbel, 2021)). The compressor models are applied in chapter 3 to calculate isentropic and volumetric efficiencies for various operating conditions. In Chapter 2.2, the modelling approach of the rolling piston-type compressor is presented. First transient simulation results are summarized in Chapter 2.3.

2.1. State of the Art: Compressor Construction Forms and Efficiencies

In this paper, we compare the performance of a rolling piston-type compressor to a reciprocating piston compressor according to their isentropic and volumetric efficiencies with respect to different pressure ratios and rotational speeds. In order to reasonably compare both compressor construction forms, we use the same thermodynamic model as presented in Göbel et al. (Göbel, 2021). The key differences are the geometry and the dynamics of the compressors. The model in Göbel et al. is based on an approach, which was implemented in Python by Roskosch et al. (Roskosch, 2018) and has been validated experimentally. In both compressor models, the compression process is described with respect to heat pump applications. However, reciprocating piston-type compressors are not common in residential heat pumps. Therefore, we present the differences between reciprocating-type and rolling piston-type compressors and extend the simulation model of Göbel et al. for the rolling piston-type compressors.

During operation, reciprocating piston-type compressors differ from rolling piston-type compressors. Hence, different characteristics regarding rotational speed, pressure ratios, performance classes, and mainteinance, design and oil issues exist. The main differences are summed up in Table 1. The comparison of different characteristics imply that rolling piston-type compressors are advantageous in the application of residential buildings.

Table 1: Main characteristics of reciprocating and rolling piston-type compressors (Eifler, 2009), (Stewart, 2019).

Characteristic	**Reciprocating-type**	**Rolling-type**
Rotational speed	Low, due to inertia forces	Higher
Volumetric losses	High	Low
Performance classes	Wide range	Only small to average pressure ratios, lower performance classes
Maintanance	Simple, accessible	Difficult, compressor is built into the casing
Design	Robust	Light
Lubricant leakage issues	High	Low

In order to compare the performance of both compressor construction forms, isentropic and volumetric efficiency for different fluids, pressure ratios, rotational speeds and states are calculated. We calculate the isentropic efficiency $\eta_{\mathrm{C}}^{\mathrm{is}}$ according to equation Eq. (1) as a function of the discharge enthalpy h_{outlet}, the inlet enthalpy h_{inlet} and the isentropic specific work ($h_{\mathrm{outlet}}^{\mathrm{is}} - h_{\mathrm{inlet}}$):

$$\eta_{\mathrm{C}}^{\mathrm{is}} = \frac{\int \dot{m}_{\mathrm{outlet}}\,\mathrm{d}t \left(h_{\mathrm{outlet}}^{\mathrm{is}} - h_{\mathrm{inlet}}\right)}{\int \dot{m}_{\mathrm{outlet}}\,h_{\mathrm{outlet}}\,\mathrm{d}t - h_{\mathrm{inlet}} \int \dot{m}_{\mathrm{inlet}}\,\mathrm{d}t} \quad \text{Eq. (1)}$$

Since the enthalpy at the compressor outlet is not constant during the discharge process, we integrate it along the discharge time interval dt according to Göbel et al. (Göbel, 2021). An analogous procedure is used for volumetric efficiency:

$$\lambda_{\mathrm{C}} = \frac{\int \dot{m}_{\mathrm{inlet}}\,dt}{V_0\,\rho_{\mathrm{inlet}}} \quad \text{Eq. (2)}$$

In Eq. (2), V_0 denotes the displacement volume of the piston, ρ_{inlet} the density at the compressor inlet and $\int \dot{m}_{\mathrm{inlet}}\,dt$ describes the time integral of the mass flow during the suction process $\dot{m}_{\mathrm{outlet}}$ denotes the outlet mass flow. Both performance measures are evaluated in Chapter 3 with respect to the rolling piston-type (ROP) and the reciprocating piston-type (REP) compressor.

2.2. Rolling Piston-Type Model (ROP)

Since both simulation models use the same thermodynamic model, we can compare differences of the construction form on isentropic efficiency and volumetric efficiency concerning certain thermodynamic states. For further applications, the thermodynamic model must be adapted for the ROP compressor model, for a physically accurate heat transfer depiction. To show its influence, we assume different heat transfer (Ishii, 2000) and frictions models (Se-Doo, 2004).

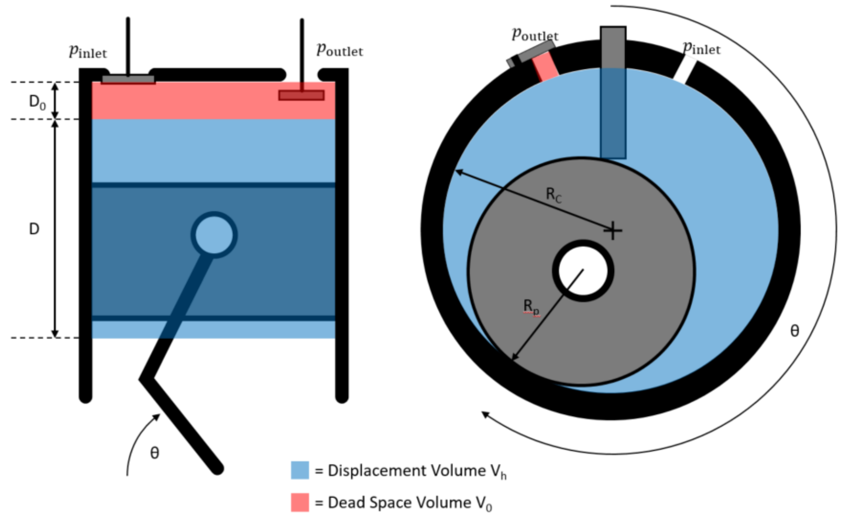

Figure 1: Geometric models for a reciprocating piston-type compressor (REP, left) and a rolling piston-type compressor (ROP, right) to illustrate the differences of the predefined compressor volumes as well as resulting compression processes.

We model the geometrical part of the ROP implementation with the following equations. The resulting system of differential and algebraic equations (DAE-System) will be written in the programming language Modelica and subsequently solved using the simulation Software "Dymola". The model is parametrized according to Table 2.

In the geometry model according to (Ooi, 1997), the rotational speed is used as an input variable to calculate the volumes as a function of time. Figure 1 schematically shows the cross-section of a ROP (right) compared to a REP (left). The right blue area represents the suction volume, while the left blue area represents the compression volume. The rolling piston with radius R_P rotates clockwise eccentrically around the centre of the cylinder with radius R_c . The separating slide presses down from on top of the piston and thus seals the two working chambers from each other. All components have the same height h. The angle Θ describes the deflection of the piston starting from the top dead centre. The time-dependent change of Θ corresponds to the angular velocity ω.

Neglecting the influence of the separating slide, the suction volume is calculated considering $a = \frac{R_c}{R_p}$ according to

$$V_S(\Theta) = \frac{hR_c^2}{2} \cdot \{(1-a^2)\Theta - \frac{(1-a)^2}{2}\sin(2\Theta) \\ -a^2 \sin^{-1}\left[\left(\frac{1}{a}-1\right)\sin(\Theta)\right] \quad - a(1-a)\sin(\Theta)\sqrt{1-\left(\frac{1}{a}-1\right)^2 \sin^2(\Theta)}\}. \quad \text{Eq. (3)}$$

The volume of the separating slide with thickness t reads

$$V_{Slide}(\Theta) = \frac{htR_c}{2} \cdot \left\{1-(1-a)\cos(\Theta) - \sqrt{(1-a)^2\cos^2(\Theta)+2a-1}\right\}. \quad \text{Eq. (4)}$$

We use the description of the displacement volume according to

$$V_h(\Theta) = \mathrm{h} \cdot \pi \cdot \left(\mathrm{R}_c^2 - \mathrm{R}_p^2\right). \quad \text{Eq. (5)}$$

Table 2: Parameters for the compressor model according to (Yanagisasawa, 1983).

Parameter	Value and Unit
Cylinder radius R_c	27 mm
Rolling piston radius R_P	23.4 mm
Piston height h	23.8 mm
Displacement volume V_h	13.6 cm³
Dead space volume V_d	0.2 cm³
Inlet (Outlet) valve diameter	8.0 (7.0) mm

2.3. Simulation Results

Applying this ROP compressor model and the REP compressor model in Göbel et al. (Göbel, 2021) to various boundary conditions, we can show their deviating time-dependent behaviour due to different compressor geometries. Time-dependent displacement volumes in both compressors impact the refrigerant mass within the chamber, its pressure, and its temperature. Adopting the rates of change, we are able to identify the resulting differences in isentropic and volumetric efficiency in Chapter 3. For future work, further geometries like scroll and screw compressor might be implemented as well.

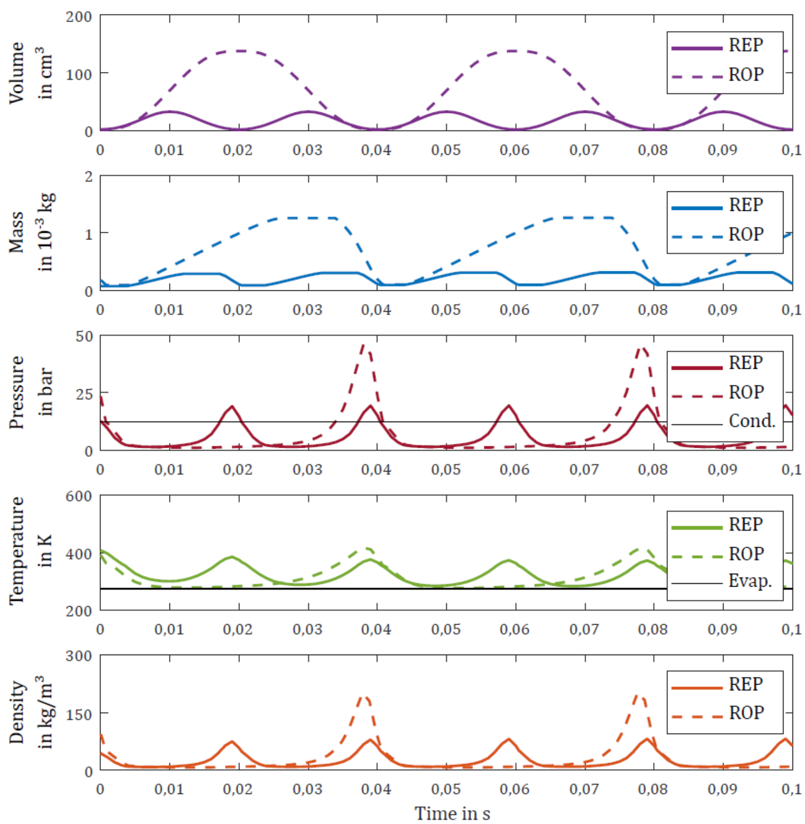

Figure 2: Dynamic behavior of a reciprocating piston-type compressor (REP, dashed line) and a rolling piston-type compressor (ROP, full line) to illustrate different operation conditions.

3. COMPARISON OF EFFICIENCIES

The isentropic and volumetric efficiencies are calculated with respect to thermodynamic inlet and outlet states, pressure ratio and rotational speed for the REP and ROP compressor model. Both models can compute fluid property models for R134a, R410A, R32, R744 and R290 presented in the open-source library presented in Vering et al. (Vering, 2020). Within this paper, we show the results for both compressors for R134a.

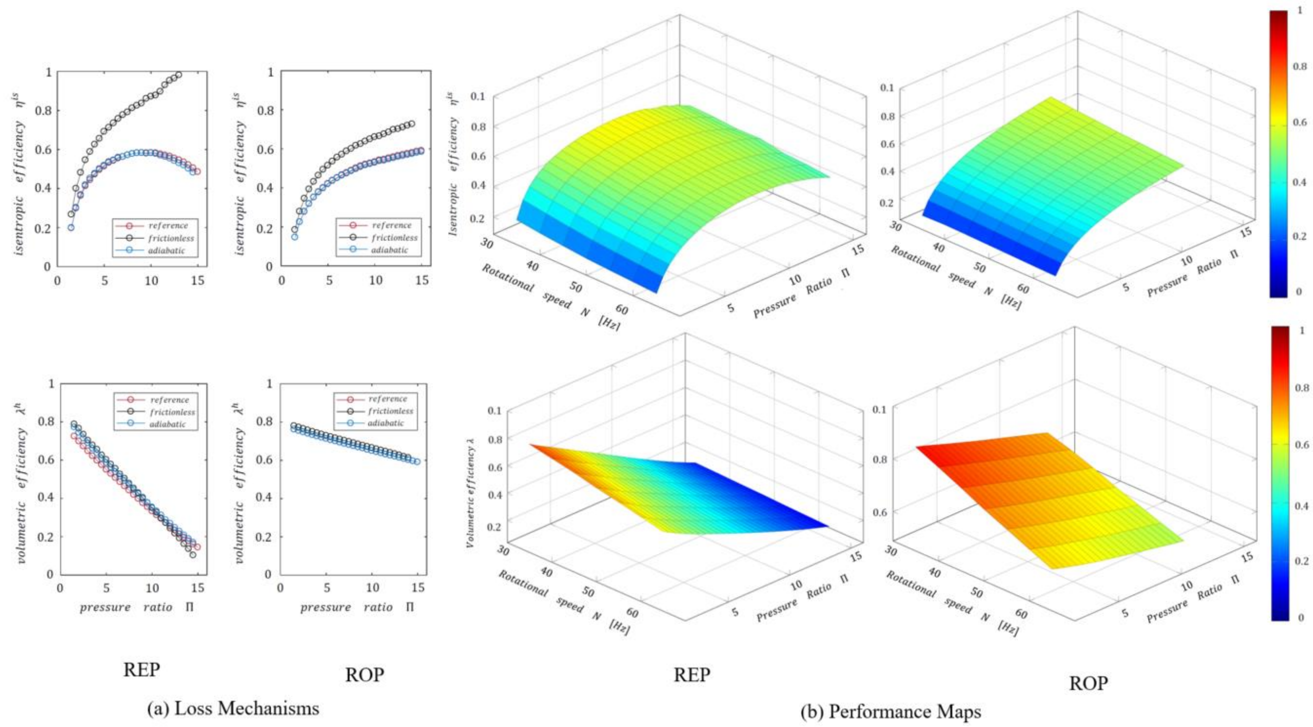

Figure 3: (a) Influence of adiabatic and frictionless compression compared to the reference case for a REP and a ROP on isentropic and volumetric efficiency. (b) Performance maps of both compressor types for different rotational speeds and pressure ratios. The refrigerant is R134a.

In Figure 3 (a) we prove the implemented loss mechanisms compared to ideal boundary conditions. The first assumption is an adiabatic compression. The second one calculates the compression frictionless. We compare these special cases to the reference using the refrigerant R134a in this paper. The results indicate on the one hand that the difference for both efficiencies between the reference process and an adiabatic compression hardly differ. On the other hand, we show, that friction has a larger impact on the isentropic efficiencies compared to the volumetric efficiency. In addition, the effects on the REP efficiencies are higher than on the ROP, which fits the characteristics in Table 1. In further studies, the models need to be calibrated against experimental data, to prove, if the heat transfer model was well-chosen. On the other hand, the effects of interaction with the lubricant need to be investigated as well.

In order to compare the impact of the compressor construction form on both efficiencies, we calculated the efficiency maps of both compressors with respect to certain rotational speeds and pressure ratios, which are summarized in Figure 3 (b). According to Table 1, we show the larger impact on volumetric efficiency on the ROP than on REP model. In addition, those efficiencies are in general on a higher level since the minimum of $\lambda_{\mathrm{ROP}} = 0.55$, whereas $\lambda_{\mathrm{REP}} = 0.10$, respectively.

Focusing isentropic efficiencies, both models predict reasonable progressions as function of pressure ratio and rotational speed. Again, the influence of pressure ratio is larger in both efficiencies than the influence of rotational speed as expected. The REP model calculates the typical parabolic progression for isentropic efficiency with respect to the pressure ratio. The ROP model, however, shows an increasing behavior. The maximum efficiency of $\eta_{\mathrm{C}}^{\mathrm{is}} = 0.6$ in both cases is almost equal regarding a pressure ratio for the REP (ROP) model at 9 (15).

4. CONCLUSION AND OUTLOOK

Within this work, we developed a dynamic simulation model that predicts the behavior of a rolling piston-type compressor. An existing model of a validated reciprocating-type compressor serves as a comparison basis. We adapt the construction form and model the geometry according to time-dependent volumes.

Parametrising the model to an existing rolling piston-type compressor, we simulate the model with transient boundary conditions to show the capability of predicting its dynamic behavior. Therefore, the refrigerant R134a was used from an open-source library. The model calculates the states of changes and can be applied to other fluid property models as well.

Two loss mechanisms were investigated to analyse the effects of adiabatic and frictionless compression. The results show that adiabatic compression shows no significant deviation from the reference case. Friction has a major impact on the isentropic efficiency. Removing friction in the simulation increases the isentropic efficiency by up to 10 % depending on the load point. We conclude to validate the heat transfer model and use both models with further refrigerants to improve the understanding of compression processes.

Lastly, we computed compressor performance maps to show the dependency of the construction form, pressure ratio and rotational speed on isentropic and volumetric efficiency. The predictions of both models show reasonable results. To apply these models in further studies, they can be validated by experimental data. In order to improve the pre-design process of heat pumps in future, it must be possible to predict the compressor efficiency as a function of the operating point and refrigerant. Therefore, additional compressor types (scroll and screw compressor) should be implemented to find the optimal compressor construction form concerning the application. We have taken the first steps here and will drive this topic forward more strongly in the future.

ACKNOWLEDGEMENTS

This work emerged from the IBPSA Project 1, an international project conducted under the umbrella of the International Building Performance Simulation Association (IBPSA). Project 1 will develop and demonstrate a BIM/GIS and Modelica Framework for building and community energy system design and operation.

REFERENCES

Cimmino, M., Wetter, M., 2017. Modelling of Heat Pumps with Calibrated Parameters Based on Manufacturer Data. Presented at the The 12th International Modelica Conference, Prague, Czech Republic, May 15-17, 2017, pp. 219–226.

Eifler W., Schlücker E., Spicher U., and Will G., Küttner Kolbenmaschinen: Kolbenpumpen, Kolbenverdichter, Brennkraftmaschinen. Vieweg + Teubner, Wiesbaden, 7. Auflage Edition, 2009.

Europäische Komission. CO2-arme Wirtschaft bis 2050, Version 2018.

Göbel S., Vering C., Venzik V., Nürenberg M., Müller D., Evaluating of refrigerants using a dynamic reciprocating compressor model, submitted paper to Compressors Conference 2021.

Ishii N., Morita N., Kurimoto M., Yamamoto S., and Sano K, Calculations for Compression Efficiency Caused by Heat Transfer in Compact Rotary Compressors. 2000.

Kelly J. A., Fu M., and Clinch J. P., Residential home heating: The potential for air source heat pump technologies as an alternative to solid and liquid fuels. Energy Policy, 98:431–442, 2016.

Navarro, E., Granryd, E., Urchueguía, J.F., Corberán, J.M., 2007. A phenomenological model for analyzing reciprocating compressors. International Journal of Refrigeration.

Navarro-Peris, E., Corberán, J.M., Falco, L., Martínez-Galván, I.O., 2013. New non-dimensional performance parameters for the characterization of refrigeration compressors. International Journal of Refrigeration 36, 1951–1964.

Ooi K. T. and Wong T. N., A Computer Simulation of a Rotary Compressor for Household Refrigerators. Applied Thermal Engineering Vol. 17, pages 65–78, 1997.

Roskosch, D., Venzik, V., Atakan, B., 2017. Thermodynamic model for reciprocating compressors with the focus on fluid dependent efficiencies. International Journal of Refrigeration 84, 104–116.

Roskosch D., Spezielle Methoden der Fluidauswahl und ihre Anwendungsmöglichkeiten am Beispiel von Wärmepumpen und Strom-Wärme-Strom-Speichersystemen. Dissertation, Universität Duisburg-Essen, Duisburg, 2018.

Se-Doo O., Jong-Woo K., and Young-Ze L., Friction and Wear Characteristics of TiN Coated Vane for the Rotary Compressor in a R410A Refrigerant. Tribology Transactions, 47(1):29–33, 2004.

Stewart M., Rotary compressors. In M. Stewart, Editor, Surface production operations, pages 847–856. Gulf Professional Publishing, Cambridge, MA, United States, 2019.

Venzik, V., Roskosch, D., Atakan, B., 2017. Propene/isobutane mixtures in heat pumps: An experimental investigation. International Journal of Refrigeration 76, 84–96.

Vering C., Engelpracht M., Nürenberg M. and Müller D., An open-source Modelica library for design and control: Modular and scalable heat pump models using natural refrigerants, Gustav Lorentzen Conference 2020, Kyoto.

Umweltbundesamt. Energieverbrauch nach Energieträgern, Sektoren und Anwendungen, 2018.

Yanagisasawa T. and Shimizu T., Influence of Clealance Volume on the Performance of the Rolling Piston Type Rotary Compressor. Bulletin of JSME, 26(214):537–544, 1983.