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Comparison of correlations for modelling heat exchanger performance in a compact ammonia refrigeration unit

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ABSTRACT

This paper compare the correlations for heat transfer coefficient that can be used for modelling performance of plate heat exchangers when used in compact ammonia chillers. A 27 kW ammonia chiller was used to collect data of four different operating conditions. After that, the most representative data from the system were used to validate a numerical model of the chiller. The model simulated the performance using several correlations of heat transfer coefficient. The results showed that a suitable combination of heat transfer coefficient correlations for refrigerant and water to calculate the heat flow rate through the evaporator could yield a deviation between -16 % and -12 % when compared against experimental data. In the case of the condenser, the correlations presented a deviation between -9.9 % and -6.1 % in heat flow rate.

Keywords: Ammonia, Chiller, Correlations, Numerical Model.

1. INTRODUCTION

The foreseen growth of cooling demand due to population growth and the effects of global warming impose a challenge for the energy sector since energy use will increase if sustainable policies and more efficient technologies are not implemented. Also, there is a forthcoming phase-down of refrigerants with high Global Warming Potential encouraged by initiatives like the Kigali Amendment. Therefore, manufacturing companies of cooling technologies are challenged to design and produce more sustainable systems. Energy-efficient cooling technologies using natural refrigerants such as ammonia will be a suitable solution to satisfy future cooling demands. Nonetheless, its toxicity and the harmful effects that leakages may have in humans have been a drawback to implement these systems in smaller capacity applications. According to (Ciconkov and Ayub, 2009) researchers and companies recognise refrigerant charge minimisation as one of the main initiatives to embrace the use of ammonia systems. The use of plate heat exchangers might decrease the amount of refrigerant due to their reduced internal volume, as explained by (Primal and Lundqvist, 2005). However, as presented by (Pearson, 2014), inappropriate charge minimisation procedures can have a counterproductive effect on the operation of the systems. Thus, the performance of these components under different operating must be assessed to guarantee reliable operation of the system.

By using a numerical model, this paper present a theoretical study describing the performance of ammonia systems at different operating conditions. For accurate modelling of a chiller, this requires correlations for heat transfer coefficient for ammonia and water to obtain reliable results at varying operating conditions. The literature presents multiple correlations developed for various refrigerants and heat exchanger geometries commonly used in refrigeration units. They can be categorised into single-phase and two-phase flow; the latter being identified for condensation or evaporation. Therefore, this paper assesses the accuracy of using different correlations in the development of a suitable and validated numerical model to study the performance of plate heat exchangers that are used in ammonia systems. A 27 kW ammonia chiller operated in multiple conditions was used to collect data which were used to validate a numerical model developed to study the performance of the chiller based on different heat transfer correlations. As a result, the set of correlations that provides the most accurate results when used for ammonia condensers and evaporators is presented in this study.

2. METHOD

This section first describes the chiller used to collect the desired data and the experimental procedure employed for testing and conducting data acquisition of the system. After that, the screening method to evaluate the different correlations for evaporation and condensation is explained. Finally, a concise description of the numerical models and the input data necessary to run the simulations is presented.

2.1. Description of the system

The system analysed in this paper and presented in Fig. 1 is a 27 kW water-to-water ammonia chiller with a direct expansion evaporator. A reciprocating compressor drives the system in conjunction with a variable frequency drive; thus, different operating conditions can be adequately regulated. The chiller has plate heat exchangers as condenser and evaporator due to the desire for a compact system.

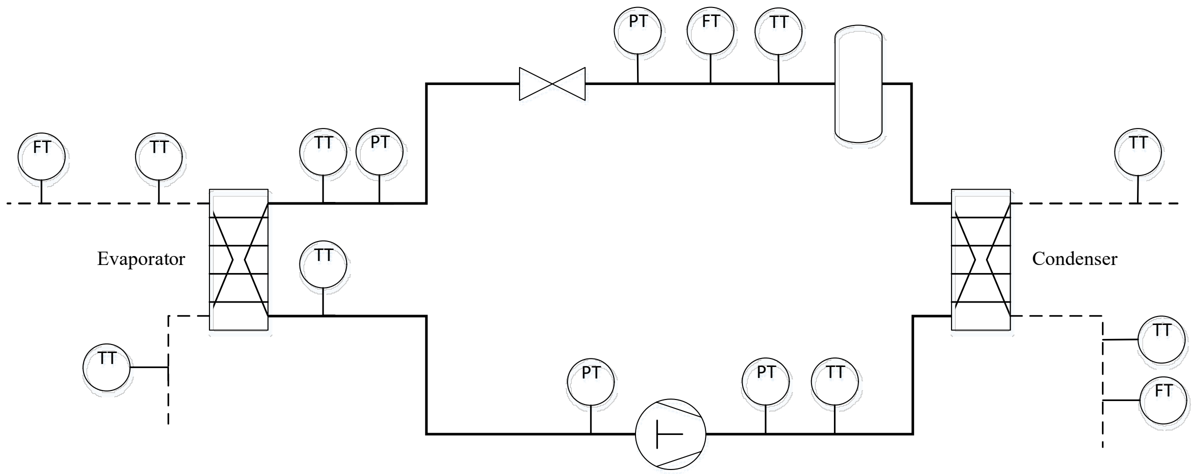

Figure 1. PI-diagram of the analysed system

Table 1 shows the physical specifications of both heat exchangers. The chiller also has a high-pressure receiver of 0.42 L of capacity that allows allocation of the refrigerant when working at different operating conditions.

Table 1. Plate heat exchanger specifications

Heat Exchanger	Nominal Heat Load [kW]	Heat Transfer area [m^2]	# Plates	Plate Width [mm]	Port to port Length [mm]
Evaporator	27	2.24	40	124	478
Condenser	32	0.45	24	90	279

The chiller has multiple sensors to measure temperature, pressure and mass flow rate on both refrigerant and water side. Thus, all the required data to validate the numerical models of the system can be collected. Table 2 presents the accuracy of the sensors that will be used to calculate the uncertainty on the heat transfer calculation when using the data.

Table 2. Accuracy of the sensors

Sensor	Temperature	Pressure	Water flowmeter	R717 mass flow meter
Accuracy	±0.3 °C to ±0.8 °C For 0 °C to 100 °C	±0.3 %	±0.3 %	±0.1 %

The test procedure aimed at maintaining the water temperatures constant in the evaporator but changing the cooling load by decreasing the operating frequency in the compressor and the water flow rates. Moreover, on the condenser, water temperatures were also maintained. Thus, the saturation pressures in both evaporation and condensation were conserved at different working conditions, and as a consequence, the pressure ratio of the system was constant during the study. Table 2 presents the desired fixed operating conditions used during the data acquisition procedure.

Table 3. Test conditions of the chiller.

Condenser			Evaporator		
P_{con} [bar]	T_{water_inlet} [°C]	T_{water_outlet} [°C]	P_{ev} [bar]	T_{water_inlet} [°C]	T_{water_outlet} [°C]
15	16	40	5.9	20	10

The heat transfer correlations were formulated based on the mass flux *G* of the plate heat exchanger channel. Thus, varying the compressor frequency along the data gathering procedure allowed the evaluation of the usability of the correlations under different working conditions. Furthermore, in reality, the system will supply lower capacities than the nominal design capacity; hence, performance in part-load operation is crucial in the development of these cooling systems. For these reasons, aside from the nominal operating frequency of 40 Hz, the testing procedure was performed at 35 Hz, 30 Hz and 25 Hz.

2.2. Numerical model and screening of correlations

A numerical model implemented in Matlab R2020a was developed to study the performance of the chiller when working at the operating conditions presented in Table 1. Ammonia properties from REFPROP 10 were used for the simulations. For the evaporator and condenser, the models utilised a 1D-discretization approach with a Newton-Raphson solver in which the plate heat exchanger was divided into control volumes. Thus, the transition between single-phase and two-phase flow that takes place inside the heat exchanger was simulated in detail. Mass and energy balances, as well as heat transfer equations between ammonia and water, were formulated for each control volume. In both condenser and evaporator, it was required to use one single-phase (SP) correlation for the superheated gas section and a two-phase (TP) correlation for the phase change section. For both ammonia and water in single-phase, the correlations from (Martin, 1996), (Khan et al., 2010), (Longo and Gasparella, 2007), (Kim and Park, 2017) and (Wanniarachchi. A.S. ; Ratnam, 1995) were identified as possible options for the current application. In the case of evaporation and condensation, the heat transfer coefficient was calculated for each control volume, meaning that the correlations were used to calculate the local heat transfer coefficient. Thus, an initial screening took place to assess the applicability of the correlations for the current model. The screening was performed by solving the correlations for a vapour quality range from 0 to 1 at different refrigerant mass flux. For evaporation, several correlations reported by (Ayub et al., 2019) as well as the correlation developed by (Arima et al., 2010) were tested with the proposed screening procedure before being used in the current numerical models. In the same way, for the condensation process, the correlations reported by (Tao and Infante Ferreira, 2019) and the one developed by (Tao and Infante Ferreira, 2020) were tested. The correlations identified as suitable were used in the simulations of the system.

2.3. Simulations

To perform the simulations, the model required the physical specifications of the system as inputs. Moreover, the operation frequencies of the compressor and the test conditions presented in Table 3 were required. Finally, the mass flows of ammonia and water obtained from the data were used as inputs for the simulations. The heat flow rate in both evaporator and condenser was calculated by use of the selected correlations. The simulation results were compared with the calculated results based on the data collected from the experiments. The deviation between the calculation and the experiments was used to assess which set of correlations yields the most accurate results to study the performance of the proposed system.

3. RESULTS

The mass flow rate of refrigerant obtained from the testing procedure, as well as the specifications from the plate heat exchangers, were used to calculate the refrigerant mass flux through the evaporator and condenser at different operating frequencies as presented in Table 4.

Table 4. Ammonia mass flow rate and mass flux through the evaporator and condenser

Frequency [Hz]	$\dot{m}_A$ [kg/h]	G_{A_ev} [kg/s·m^2]	G_{A_con} [kg/s·m^2]
25	54	2.9	17.2
30	65	3.6	21.0
35	77	4.3	24.8
40	88	4.9	28.4

The measurements of water mass flow rate were used to calculate the heat transfer in both evaporator and condenser. Table 5 shows the results at different operating conditions and the uncertainty of the calculation.

Table 5. Water mass flow rate and heat flow rate.

Frequency [Hz]	$\dot{m}_{W\_ev}$ [kg/h]	$\dot{Q}_{ev}$ [kW]	Uncertainty [%]	$\dot{m}_{W\_con}$ [kg/h]	$\dot{Q}_{con}$ [kW]	Uncertainty [%]
25	1399	16.8	4.0	727	19.1	2.8
30	1728	20.3	3.9	809	23.4	2.7
35	2056	23.9	3.9	974	27.8	2.7
40	2381	27.0	3.9	1103	32.2	2.7

The screening process excluded several correlations that were not suitable for calculating the local heat transfer coefficient for ammonia. Figure 2a shows the screening result of the correlation proposed by (Ayub et al., 2019), which was developed for evaporation of ammonia in plate heat exchangers. Figure 2b shows the result of the screening procedure of the correlation proposed by (Yan et al., 1999), developed for condensation of R134a inside plate heat exchangers.

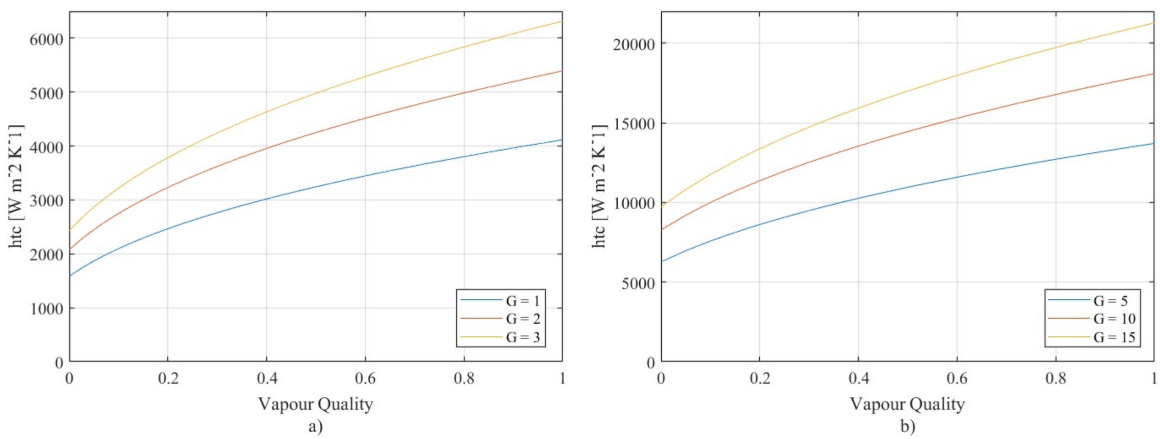

Figure 2. Screening of evaporation and condensation correlation

Table 6 compiles the correlations selected as possible candidates to simulate the performance of plate heat exchangers used as evaporator and condenser of ammonia systems.

Table 6. Selected correlations for evaporation and condensation

Evaporation	(Amalfi et al., 2016)	(Ayub et al., 2019)	(Khan et al., 2014)	(Danilova et al., 1981)	(Arima et al., 2010)
Condensation	(Yan et al., 1999)	(Longo, 2008)	(Arman and Rabas, 1995)	(Tao and Infante Ferreira, 2020)	-

The simulations of the chiller at different operating frequencies were performed, and the combinations of correlations that yielded the lowest deviation on the heat transfer when compared with the experimental data were determined. The results are presented in Table 7 for the evaporator and Table 8 for the condenser.

Table 7. Simulation results obtained for the evaporator

Frequency [Hz]	$\dot{Q}_{ev}$ [kW]	SP-R717	TP–R717	SP-Water	$\dot{Q}_{model}$ [kW]	Deviation [%]
25	16.8	Khan	Arima	Martin	14.1	-16.0
30	20.3	Longo	Arima	Khan	17.8	-12.2
35	23.9	Longo	Arima	Khan	20.8	-13.0
40	27.0	Longo	Arima	Khan	23.6	-13.1

Table 8. Simulation results obtained for the condenser

Frequency [Hz]	$\dot{Q}_{con}$ [kW]	SP-R717	TP–R717	SP-Water	$\dot{Q}_{model}$ [kW]	Deviation [%]
25	19.1	Kim and Park	Yan	Kim and Park	17.2	-9.9
30	23.4	Longo	Arman	Longo	21.6	-7.5
35	27.8	Kim and Park	Arman	Longo	25.4	-8.4
40	32.2	Kim and Park	Arman	Longo	30.3	-6.1

4. DISCUSSION

The screening process discarded correlations that were not suitable to calculate the local heat transfer coefficient. A reason for the inapplicability of these correlations is the method used to formulate them. For instance, the use of the convection number will force the calculation of the local heat transfer coefficient to tend to infinity at lower vapour qualities. Conversely, it will also force the calculation to tend to zero when reaching high vapour qualities. The simulations showed the combination of correlations for calculating the overall heat transfer coefficient, which produced the most reliable heat flow rate estimation. Nonetheless, the proposed method does not determine which correlations provide the most accurate estimation of the heat transfer coefficient of ammonia and water when taken separately.

In the study performed by (Djordjevic and Kabelac, 2008), some correlations were tested to assess its applicability to estimate the local heat transfer coefficient of ammonia during evaporation and values of G above 10 [kg/s·m^2]. From an experimental procedure, (Djordjevic and Kabelac, 2008) concluded that at lower mass fluxes and high values of vapour qualities, the heat transfer coefficient of ammonia drops down. Moreover, (Djordjevic and Kabelac, 2008) did not recognise a correlation capable of handling this variation. However, when performing the proposed screening procedure, it was determined that the correlation of Arima adequately capture the behaviour exhibited by (Djordjevic and Kabelac, 2008) and elucidates why this correlation performed better than the other four correlations considered. For the condensation process, Arman and Yan were not developed for ammonia systems or to calculate local heat transfer coefficient. In contrast, the only correlation developed for local heat transfer coefficient of ammonia during condensation (Tao and Infante Ferreira, 2020) tended to over predict the heat flow rate when used in conjunction with all of the single-phase correlations considered in this study. Still, the deviation of the calculation was not much higher than the reported values with the selected correlations of Arman or Yan.

5. CONCLUSIONS

This paper compare the correlations which were determined to be applicable for calculation of heat transfer coefficient of refrigerant in single-phase and two-phase flow for modelling performance of compact ammonia chillers. A numerical model was validated against data from a 27 kW ammonia chiller. This procedure showed that a suitable set of correlations for the evaporator could yield a deviation on the heat flow rate calculation between -16 % and -12 % when working at different cooling capacities. In the case of the condenser, the correlations presented a deviation between -9.9 % and -6.1 % in prediction of the heat flow rate.

NOMENCLATURE

G	mass flux (kg·s^{-1}·m^{-2})	$\dot{m}$	Mass flow rate (kg·s^{-1})
P	pressure (bar)	$\dot{Q}$	Heat flow rate (kW)
SP	Single Phase	T	temperature (°C)
TP	Two Phase		

Subscripts

A	ammonia	con	condenser
ev	evaporator	W	water

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