Proceedings of the 16th UK Heat Transfer Conference (UKHTC2019)
8-10 September 2019, Nottingham

UKHTC2019-121

Modelling and Evaluation of the Thermohydraulic Performance of Finned-Tube Supercritical Carbon Dioxide Gas Coolers

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1. INTRODUCTION

Supercritical carbon dioxide (sCO_2) is becoming an important commercial and industrial fluid due to its environmental credentials and its advantageous characteristics, such as being nontoxic and non-flammable and having low viscosity and a large refrigeration capacity. Thermodynamic systems using sCO_2 as the working fluid have been widely studied in many engineering applications, such as refrigeration and heat pumps, and power generation and conversion systems. In these systems, the thermohydraulic performance of gas coolers has a significant influence on the system efficiency. The understanding of the thermohydraulic performance under different operating conditions is essential for design and optimization purposes. To achieve this objective, Yin et al. [1] and Asinari et al. [2], respectively developed a first principles-based model and a fully three-dimensional simulation model for microchannel gas coolers. Ge et al. [3], Gupta et al. [4], Marcinichen et al. [5] and Singh et al. [6] proposed detailed mathematical models utilizing distributed methods for finned-tube gas coolers. Li et al. [7, 8] developed a simplified mathematical model for an air-cooled coil gas cooler. In this paper, a detailed mathematical model employing the distributed modelling approach and the *ε-NTU* method is discussed, and the thermohydraulic performance of two finned-tube sCO_2 gas coolers [9], is investigated.

2. METHDOLOGY

Figure 1 demonstrates the distributed method (segment by segment) design for the two finned-tube sCO_2 gas coolers. Gas cooler A has 3 tube rows with 8 tubes per row, and gas cooler B, 2 tube rows, and 16 tubes per row. The finned copper tubes have 8 mm outer diameter, 0.68 mm wall thickness and 1.6 m length. The thickness of the wavy aluminum fins is 0.16 mm and the fin spacing 2.12 mm. For the model, each tube is divided into 20 equal segments. For each segment, the *ε-NTU* method [10] is employed for the heat transfer and pressure drop calculations. The thermophysical properties of the sCO_2 and the cooling air in each segment using the NIST REFPROP v9.1 software.

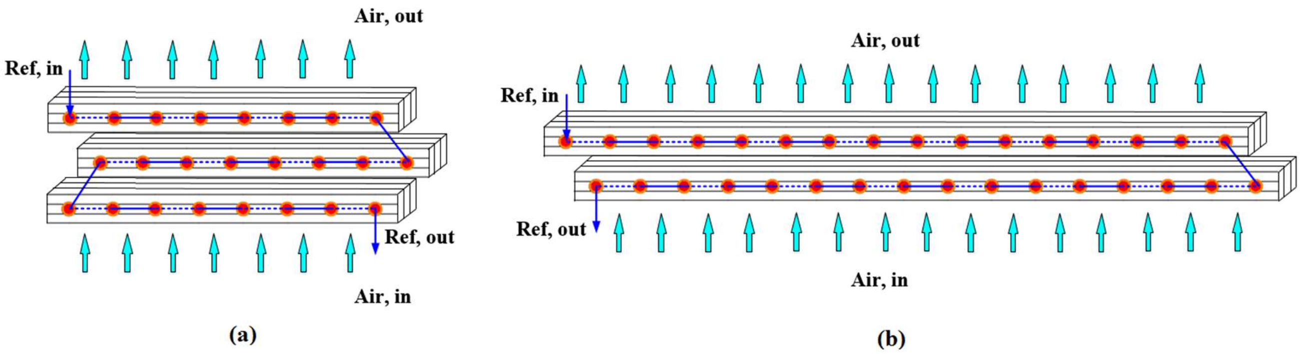

Fig. 1 Model of finned-tube sCO_2 gas cooler: (a) gas cooler A, and (b) gas cooler B.

The thermohydraulic performance of the fluid flowing over or through the tubes is calculated using empirical correlations for Nusselt number and friction factor: Krasnoshchekov and Protopopov [11] correlation for sCO_2 and Wang et al. [12] correlation for cooling air. Since the density of sCO_2 undergoes a significant change with temperature in the near-critical region, the pressure drop of sCO_2 takes into consideration the influence of flow deceleration.

3. RESULTS

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The models were verified against the experimental data from Santosa et al. [9]. The comparison between the modelling predictions and the experimental results is illustrated in Table 1. Considering the uncertainty of the K-type thermocouples and pressure transducers used in the test facility, the present modelling can predict the thermohydraulic performance of the gas coolers with good accuracy. For numbers 1-6, the sCO_2 pressure drop from the modelling $\Delta P_{ref, mol}$ are 12.5, 11.4, 11.8, 52.3, 66.2 and 70.7 kPa. Gas cooler B shows much larger pressure drop but similar heat transfer rate for per unit mass flow rate of sCO_2 compared to gas cooler A with the other similar operating conditions, due to the different engineering design.

Table 1 Comparison of modelling results with experiment data

Test	Operating condition					Results					
	$v_{air, in}$ (m/s)	$T_{air, in}$ (°C)	$P_{ref, in}$ (bar)	$T_{ref, in}$ (°C)	m_{ref} (kg/s)	$\Delta P_{air, exp}$ (Pa)	$\Delta P_{air, mol}$ (Pa)	$T_{ref, out, exp}$ (°C)	$T_{ref, out, mol}$ (°C)	Q_{exp} (kW)	Q_{mol} (kW)
	Gas cooler A					Gas cooler A					
No. 1	1.7	32.8	85.1	105.5	0.0105	26.6	26.9	33.2	32.83	2.4	2.46
No. 2	2.0	32.8	84.2	99.2	0.01	34.2	34.8	32.8	32.82	2.23	2.31
No. 3	2.4	34.3	86.6	116.8	0.0103	41.4	46.6	34.9	34.31	2.4	2.43
	Gas cooler B					Gas cooler B					
No. 4	1.7	35.1	86.3	100.8	0.019	13.9	17.6	35.3	35.38	4.1	4.12
No. 5	2.0	35.2	86.5	104.6	0.0215	25.6	22.7	35.0	35.54	4.6	4.75
No. 6	2.4	33.0	83.9	101.3	0.021	27.6	30.4	33.0	33.15	4.65	4.94

Following model verification, the effect of sCO_2 mass flow rate m_{ref} on the thermohydraulic performance was investigated. For gas cooler A and test No. 3 increasing the m_{ref} by 100% increased the sCO_2 outlet temperature $T_{ref, out, mol}$ from 34.3 °C to 35.0 °C, and the heat transfer rate Q_{mol} from 2.43 kW to 4.9 kW. $\Delta P_{ref, mol}$ increases by 4 times from 11.8 kPa to 47.1 kPa. For gas cooler B and test No. 6 doubling m_{ref} increased $T_{ref, out, mol}$ from 33.2 °C to 35.3 °C, and Q_{mol} from 4.9 kW to 8.7 kW. The pressure drop $\Delta P_{ref, mol}$ quadruples from 70.7 kPa to 282.4 kPa.

The higher pressure drop in gas cooler B is due to the higher mass flow rate and total length of tubes in each row of the gas cooler. Even though the heat transfer for per unit mass flow rate is similar to gas cooler A, the higher pressure drop will lead to a higher compressor power consumption which will impact on the overall efficiency of the CO_2 refrigeration system.

4. CONCLUSIONS

To investigate the thermohydraulic performance of finned-tube sCO_2 gas coolers, a detailed mathematical model employing the distributed modelling approach and the *ε-NTU* method was developed and presented in this study. The model uses empirical correlations for the Nusselt number and friction factor for the heat transfer and pressure drop calculations on the sCO_2 and cooling air sides. The model was validated against experimental data and then employed to investigate the influence of design and operating parameters on overall gas cooler performance. The pressure drop in the gas cooler is an important parameter in the optimization of the performance of CO_2 refrigeration and heat pump systems particularly in the drive to reduce the footprint of components and the system as a whole. The model will be used as a tool in the investigation of the potential of 5.0 mm tube and microchannel heat exchangers as CO_2 gas coolers.

ACKNOWLEDGMENTS

The work presented in this paper is supported by a number of funders as follows: i) The Engineering and Physical Sciences Research Council (EPSRC) of the UK under research grants EP/P004636/1 'Optimising Energy Management in Industry - OPTEMIN', and EP/K011820/1 (Centre for Sustainable Energy Use in Food Chains) and ii) the European Union's Horizon 2020 research and innovation programme under grant agreement No. 680599, - Industrial Thermal Energy Recovery and Management – I-TERM'. The authors would like to acknowledge the financial support received from the funders and industry partners.

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