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Design Optimisation of CO_2 Gas cooler/Condenser in a Refrigeration System

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Abstract

As a natural working fluid, CO_2 has been widely applied in refrigeration and heat pump systems where heat is conventionally rereleased to ambient through external airflow. Owing to extraordinary thermophysical properties, especially its low critical temperature, the CO_2 heat release through a high-pressure side heat exchanger will inevitably undergo either supercritical or subcritical processes, depending on ambient air temperatures and head pressure controls. Correspondingly, the heat exchanger will act intermittently as either a gas cooler or condenser within the system during an annual operation. Such evidence should therefore be taken into account for an optimal design of the heat exchanger and head pressure controls in order to significantly enhance the performance of both components and the associated system.

To achieve these targets, two CO_2 finned-tube gas coolers/condensers with different structural designs and controls have been purposely built, instrumented and connected with an existing test rig of a CO_2 booster refrigeration system. Consequently, the performance of the CO_2 gas coolers/condensers with different structure designs, controls and system integration at different operating conditions can be thoroughly investigated through experimentation. In the meantime, models of the finned-tube CO_2 gas coolers/condensers have been developed using both the distributed (detailed model) and lumped (simple model) methods. The former is employed to give a detailed prediction of the working fluid temperature profiles, localized heat transfer rates and effects of pipe circuitry arrangements, while the latter is suitable for the simulation and optimisation of system integration with less computation time. Both models have been validated with measurements, and moreover the simple model has been integrated with other component models so as to create a system model. The effects of the CO_2 gas cooler/condenser sizes and controls on the system performance can thus be compared and analysed.

Keywords: *CO_2 gas cooler or condenser; test facilities; experiment and modelling; heat exchanger sizes and controls; refrigeration system*

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1. Introduction

As an environmentally friendly working fluid with extraordinary thermophysical properties, CO_2 has been readily applied in refrigeration and heat pump systems. Air cooled finned-tube condensers used in conventional refrigeration systems have also been greatly exploited in the CO_2 systems with cascade arrangements or all-CO_2 transcritical structures of which the CO_2 heat exchangers operate as either condensers or gas coolers, depending on ambient conditions and head pressure controls. Therefore, it is demonstrable that due to the low critical temperature and very high critical pressure of the CO_2 fluid, a CO_2 refrigeration system can periodically operate between high performance subcritical cycles to less efficient transcritical cycles. However, this operating efficiency can be significantly improved through the use of an expansion turbine, a liquid-line/suction-line heat exchanger (llsl-hx), and system equipment such as a compressor, evaporator or gas cooler [1], as well as optimal controls of refrigerant high-side pressures [2]. The feasibilities of such strategies can be substantiated through system experiment and modelling.

Although the performances of CO_2 finned-tube gas coolers or condensers have been investigated extensively using both experimental and theoretical methods, research on the effect of their integration with associated systems is still rather limited. To some extent, this could lead to inaccurate design and mismatching of the heat exchanger size and control when it is applied into a real system. The combined analysis of the heat exchange within the system can also contribute towards the selection and design of other matched components and appropriate system controls.

In this paper, the performance of the CO_2 gas cooler or condenser has been investigated experimentally in a purposely-built CO_2 gas cooler test rig, which is connected to a CO_2 transcritical booster refrigeration test facility. In the meantime, models of the finned-tube CO_2 gas cooler and condenser have been developed using lumped and distributed methods which are both validated with the corresponding test results. The simple (lumped) model is then integrated with other component models and specifications to establish a system model. Consequently, the effects of the heat exchange sizes and pipe circuitry arrangements on the system performance and controls at different operating states may be examined, compared and analysed.

2. Experimental facilities

A test rig has been built, as shown in Figure 1, to experimentally examine the performance of CO_2 gas coolers or condensers using different sizes and operating conditions. In this test rig, the CO_2 heat exchanger is suspended tightly between two upright metal frames; a propeller air fan with variable speed control is installed above the heat exchanger to maintain fixed air flow; above that are a number of smaller opposing air fans along the length of the pipe which switch on if the air-on temperature is controlled to be higher than ambient. As such, part of the hot exhaust air will flow back through the return air tunnels to the return air grills and mix with lower temperature ambient air flow. Should the mixed air flow temperature be lower than the designed air-on temperature, an electric air heater installed just below the heat exchanger will maintain the air on temperature. The test rig has been instrumented comprehensively to detailed measurement data as well as the overall performance description of the heat exchanger itself and its integrated CO_2 refrigeration system. These include two thermocouple meshes with 24 points each to measure air-on and air-off temperatures, pressure differences in air flow through the heat exchanger to attain an air-side pressure drop, and air flow velocity to obtain the air flow rate. For the refrigerant side, four pressure transducers are installed inside the inlet and outlet headers and one circuit of the heat exchanger in order to measure the overall and heat exchanger refrigerant side pressure drops. In addition, as shown in Figure 2, a large number of thermocouples are attached on all the pipe bends along the pipes of each circuit to measure refrigerant temperature variation or profiles from inlet to outlet in a circuit.

The tested gas cooler/condenser is connected and integrated with a CO_2 boost refrigeration system so as to pass through the refrigerant flow with a constant flow rate and specific superheated parameters from the system compressors. All the sensors in the system are calibrated before measurement with acceptable uncertainties in which thermocouples are less than ±0.5°C, pressure transducers ±0.3% and air velocity meter ±3.0 %. These will ensure the accuracy of measurements during the test period.

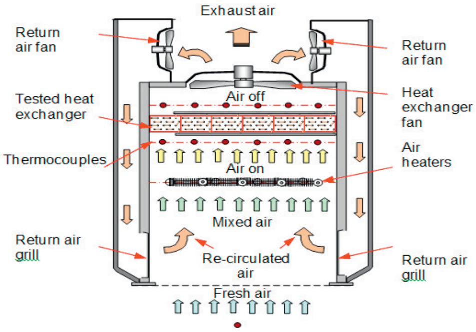

Fig. 1 test rig of CO_2 gas cooler & condenser

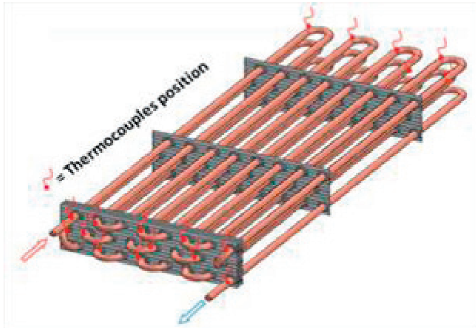

Fig. 2 pipe arrangement and thermocouple locations

3. Mathematical models and validation

The CO_2 finned-tube gas cooler/condenser can be modelled using two well-known methods: distributed and lumped. The former is a detailed model and has been developed by the authors [3], wherein the heat exchanger to be modelled is divided into a number of small segments with specified 3-D coordinates i, j and k along the directions of pipe length, longitudinal and transverse. For each piece, conservation equations of mass, momentum and energy need to be derived and applied. The detailed model applies localised correlations of heat and mass transfer coefficients and hydraulic processes such that the local parameter distribution profiles, such as temperature, pressure and heat transfer rate, of hot and cold fluid flowing along the heat exchanger can be precisely predicted. Therefore, the detailed model is rendered more accurate than any other modeling method and is more suitable for the analysis and design of complex heat exchangers with intricate pipe circuitary arrangements and uneven air flow distributions. However, it requires a longer computation time if more segments are to be divided for a modelled heat exchanger. Therefore it is not entirely appropriate for use in simulating a refrigeration system where the heat exchanger with detailed model is integrated.

Comparatively, the lumped method is a simple model in which the heat exchanger is divided into a very limited number of segments and each is described with conservation equations of mass, momentum and energy. The computation time is thus greatly reduced and it is more practical to model a system with the simple model integrated, although a model validation beforehand with test results is strictly required. The lumped method is therefore used in this paper to model the tested CO_2 gas coolers/condensers and the whole integration to examine their compatibilities in the system and controls.

As shown in Figure 4, two finned-tube CO_2 gas coolers/condensers of different sizes and pipe arrangements are experimentally investigated in the refrigeration system described above. The larger one named coil A has 3 rows, 4 pipe circuits, 96 pipes in total and overall dimension of 1.6m×0.066m×0.82m (L×D×H) while the smaller one named coil B has 2 rows, 2 circuits, 64 pipes in total and overall dimension of 1.6m×0.044m×0.82m (L×D×H). All other structural parameters are the same for both heat exchangers, including a copper pipe with an inner diameter of 6.72mm, a 0.16mm thick aluminium fin with a density of 453 fins/m . Up to 20 tests have been carried out for each of the two CO_2 heat exchangers at both gas cooler and condenser modes and various operating conditions. Correspondingly, the models with lumped methods were simulated and compared with the test results and fairly agreements have been obtained.

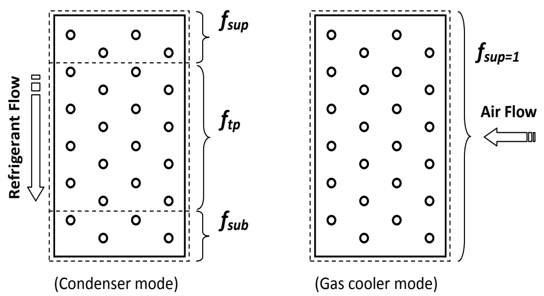

Fig. 3 single circuit heat exchanger and segment divisions

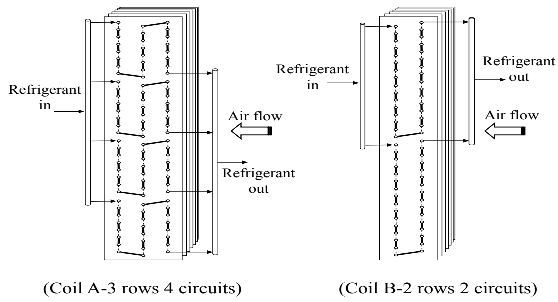

Fig. 4 two tested finned-tube CO2 gas coolers/condensers

4. Effects of heat exchanger sizes and controls

The developed CO_2 gas cooler/condenser model is then integrated into the existing CO_2 booster system to compare and analyse the effects of heat exchanger sizes and controls on the system performance under various design specifications. These include a specified evaporating temperature, superheating, cooling capacity, head pressure control, approach temperatures and transition ambient temperatures etc. As a result, the variations of controlled condenser air volumetric flow rates with ambient temperatures and supercritical pressure controls for different sizes of high pressure heat exchangers (3-row and 2-row) have been predicted, as shown in Figures 5 and 6. It can be seen that a more powerful heat release fan will be required for a smaller-size coil. On the other hand, the heat exchanger and system performance cope well with fan speed controls to compromise the impact of the heat exchanger size reduction.

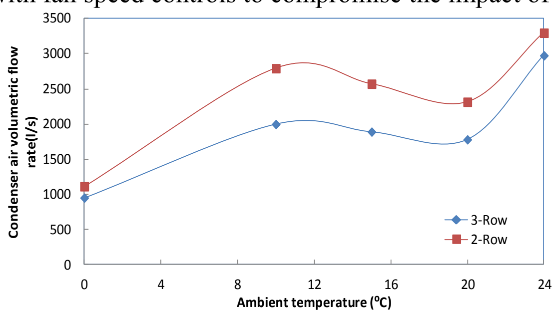

Fig. 5 variation of volumetric flow rate with ambient temperature for different CO2 condensers

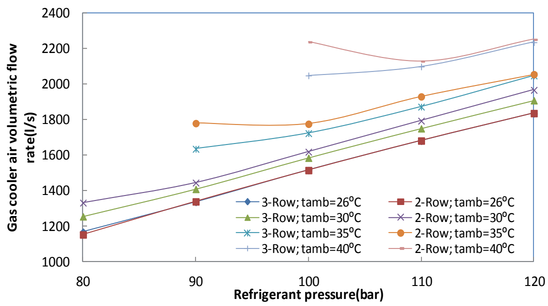

Fig. 6 variation of volumetric flow rate with ambient temperature and supercritical pressure for different CO2 gas cooler

5. Conclusions

In varying ambient air temperatures, the high pressure CO_2 heat exchanger in a CO_2 refrigeration system will alternatively operate as either a gas cooler or condenser. The heat exchanger size designs can affect the performance of both the component and the integrated system and controls. These can be predicted using a validated component model and its integration into a CO_2 system. As a result, the effect of heat exchanger sizes on system performance can be enhanced with fan speed controls.

Acknowledgement

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