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Modeling a multi-stream heat exchanger for CO_2 condensation

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ABSTRACT

Multi-stream heat exchanger is one of the most important components in CO_2 purification process, which is characterized as high efficiency, low consumption and high energy density. This work aims to develop a CFD model for a multi-stream heat exchanger, based on which the impact of the impurities on heat transfer characteristics is studied. Three streams are considered, including two streams flowing in two concentric pipes and one stream flowing perpendicularly to the pipes. Based on the model, this work calculates the pressure drop and the average heat transfer coefficient which is calculated from the average heat transfer coefficient of two interfaces formed from these three fluids. It is found that the average heat transfer coefficient and friction pressure drop have an obvious downward trend with the increase of the volume fraction of impurity gas; under the same volume fraction of impurity gas, both of them increase with the increase of refrigerant velocity.

Keywords: Impurity, Heat transfer characteristics, CO_2 condensation, Multi-stream heat exchanger

NONMENCLATURE

Abbreviations	
CCS	CO2 capture and storage
CO2	Carbon dioxide
CFD	Computational Fluid Dynamics
ρ	Density of flow
V	Velocity of flow
mwt	Mass flow of water
cpwt	The specific heat capacity of water
Two	The external wall temperature
Twi,z	The mean inner wall temperature at each position
hz	Local heat transfer coefficient
R	Wall thermal resistance
h	Average heat transfer coefficient
ΔP	total pressure drop in the tube
ΔPm	momentum pressure drop
ΔPfr	frictional pressure drop
G	Mass flow rate
ρg	Density of gas
ρl	Density of liquid

1. INTRODUCTION

Among the CCS processes, cryogenic process can be applied in CO_2 purification in oxy-fuel combustion because the CO_2 concentration in the flue gas is high and the main impurities are non-condensable gases [1]. In the CO_2 cryogenic process, the multi-stream heat exchangers for CO_2 condensation and liquefaction, is one of the most important components. For the property impacts on the condensation and liquefaction process in multi-stream heat exchangers, which are essential to non-condensable impurity removal. Multi-stream heat exchanger can not only greatly reduce the input cost of equipment, but also achieve special process, so it is widely used in petrochemical, power machinery, vehicle, electronics and other fields.

Heat exchanger can be classified on the basic of heat exchange process, geometry, number of fluids, flow arrangements etc. There are numerous experimental and numerical studies related to design and performance analysis of conventional two-stream heat exchanger. These studies mainly include different aspects of heat exchanger such as establishment of numerical model, flow arrangement and fluid flow. Valladares developed a numerical model for analyzing the behavior of triple concentric-tube heat exchangers by means of a transient one-dimensional analysis of the fluid flow governing equations and the heat conduction in solids to evaluate the shear stress and heat flux [2]. Peng et al. designed passage arrangement for multiple

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operating conditions by using hybrid particle swarm algorithm and designed a passage arrangement of a twenty-four streams heat exchanger, and some indirect comparisons are implemented to verify the proposed method [3]. D.Bhanuchandrarao et al. investigated the performance, CFD analysis of different fluids and different pipe materials on parallel and counter flow in concentric tube heat exchanger [4].

Even though there have been some works focusing on the heat transfer performance of multi-stream heat exchanger, little attention has been paid to the impact of impurity. The objective of this article is to explorer the influence of different volume fraction of impurity gas(O_2) on the CO_2 condensation, in order to provide insights and guidelines regarding the optimization of multi-stream heat exchanger in the future work.

2. MODEL DISCRIPTION

The effect of impurity gas on CO_2 condensation was studied based on a multi-stream heat exchanger model. The model of multi-stream heat exchanger used in this work is from our previous work, which was developed in SolidWorks and ICEM-CFD is used to generate the mesh. The results are obtained in Fluent after specifying the boundary conditions.

The mixture model in the CFD software can be used for two-phase flow or multiphase flow (fluid or particle). Because the phases are treated as interconnected continuities in the Euler model, the mixture model solves the momentum equation of the mixture and describes the discrete phases by their relative velocities. Applications of the mixture model include low-load particle load flow, bubble flow, sedimentation, and cyclone separators. The mixture model can also be used for homogeneous multiphase flows without discrete relative velocities.

In this paper, we use the LEE model of evaporation and condensation model to simulate the phase change in the heat exchanger. The Lee model is a mechanistic model with a physical basis. It is used with the mixture and VOF multiphase models and can be selected with the Eulerian multiphase model if one of the overall interfacial heat transfer coefficient models will be used (as opposed to the two-resistance model). In the Lee model, the liquid-vapor mass transfer (evaporation and condensation) is governed by the vapor transport equation:

$$\frac{\partial}{\partial t}(\alpha_v\rho_v)+\nabla(\alpha_v\rho_v\bar{V}_v)=\dot{m}_{lv}-\dot{m}_{vl} \qquad (1)$$

Where v is vapor quality; α_v is vapor volume fraction; ρ_v is vapor density; $\bar{V}_v$ is vapor phase velocity; $\dot{m}_{lv}$,$\dot{m}_{vl}$ is the rates of mass transfer due to evaporation and condensation, respectively. These rates use units of kg/s/m^3.

Firstly, in order to verify the applicability of the phase change model in FLUENT, condensation simulation was conducted in a two-stream heat exchanger, where the working medium was R134a. The dimension parameters of the model and the boundary conditions of the first validation are shown in Table 1. And geometry of the flow arrangement of two-stream heat exchanger is shown in Fig.1. More information of the physical model can be found in ref [5].

Table 1 Boundary conditions for two-stream heat exchanger

Parameters	Value
Refrigerant	R134a
Range of heat flux	10.49-17.17kW/m^2
Range of mass flux	42-64kg/m^2
Range of saturation temperature	44-49℃
Inner diameter of inner pipe	5.8mm
outer diameter of inner pipe	7.8mm
Inner diameter of outer pipe	22.2mm
outer diameter of outer pipe	25.6mm
Length of pipe	800mm

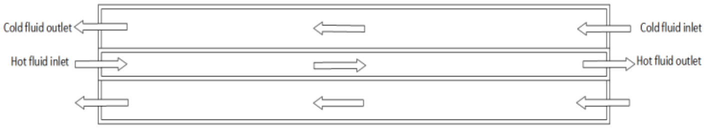


Fig.1 Flow arrangement of the two-stream heat exchanger

In this validation, two parameters from literature were selected for comparison, namely local heat exchanger coefficient and friction pressure drop. The local heat transfer coefficient(hz) is calculated by Eq.2 to Eq.7.

$$Q=m_{wt}\cdot cp_{wt}\cdot\left(T_{wt,O}-T_{wt,i}\right) \qquad (2)$$

$$q=\frac{Q}{\pi\cdot ID\cdot L} \qquad (3)$$

$$h_z = \frac{q}{T_{ref} - T_{wi}} \tag{4}$$

$$T_{wo} = \frac{T_a + T_b}{2} \tag{5}$$

$$T_{wi,z} = T_{wo} + (Q \cdot R) \tag{6}$$

$$R = \frac{ln(\frac{OD}{ID})}{2 \cdot \pi \cdot L_z \cdot k} \tag{7}$$

The friction pressure drop(d_p/d_z) is calculated by Eq.8 to Eq.11.

$$-\frac{dp}{dz} = -\frac{\Delta P}{L} \tag{8}$$

$$\Delta P = \Delta P_{fr} + \Delta P_m + \Delta P_{st} \tag{9}$$

$$\Delta P_m = G^2 \cdot (\frac{1}{\rho_g} - \frac{1}{\rho_l}) \cdot \Delta x \tag{10}$$

$$\Delta P_{fr} = \Delta P - \Delta P_m \tag{11}$$

Where ΔP is total pressure drop in tube; ΔP_m is momentum pressure drop; G is mass flow of hot fluid; ρ_g, ρ_l are density of gas and liquid respectively; Δx is the absolute value of the vapor quality change along the tube.

In order to explore the influence of impurity gas(O_2) on CO_2 condensation, the internal working medium is replaced with a mixture of refrigerant CO_2 and O_2 after the condensation in the two-stream heat exchanger validation is completed. In this simulation, the boundary conditions are shown in Table 2. And geometry of the flow arrangement of three-stream heat exchanger is shown in Fig.2. More information of the physical model can be found in ref [6].

Table 2. Dimensional parameters and boundary conditions of three-stream heat exchangers

Parameters	Value	Parameters	Value
Domain	Fluid, solid	Inner tube ’s inside diameter(mm)	10.5
Fluid	CO_2/O_2	outer tube ’s inside diameter(mm)	23
Solid	Copper	Tube thickness（mm）	1
Length of heat exchanger, L (mm)	500	Cross flow rectangular opening(mm*mm)	31*500
Hot fluid temperature(K)	300	Range of hot fluid velocity (m/s)	0.005,0.01, 0.02
Cold fluid temperature(K)	260	Cold fluid velocity(m/s)	0.005

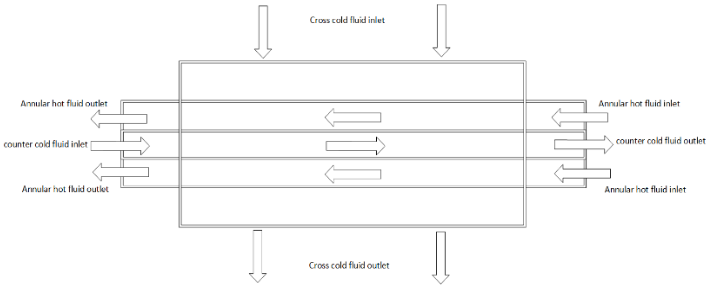


Fig.2 Flow arrangement of the three-stream heat exchanger

In this validation, two parameters are used to observe the trend of them, which include the average heat transfer coefficient(h) and the pressure drop(d_p/d_z). The average heat transfer coefficient(h) is calculated using Eq.12. The frictional pressure drop is calculated using the same equations as in the previous validation.

$$h = \frac{h_i + h_o}{2} \tag{12}$$

Where h_i, h_O are the heat transfer coefficients on the two surfaces generated by the hot fluid and the two cold fluids.

3. RESULTS AND DISCUSSIONS

In order to explore the influence of impurities on the condensation performance of multi-flow heat exchanger, the model in this paper is verified by condensation in a two-stream heat exchanger and CO_2 condensation with impurities in a three-stream heat exchanger. The following section shows the results of the two validations.

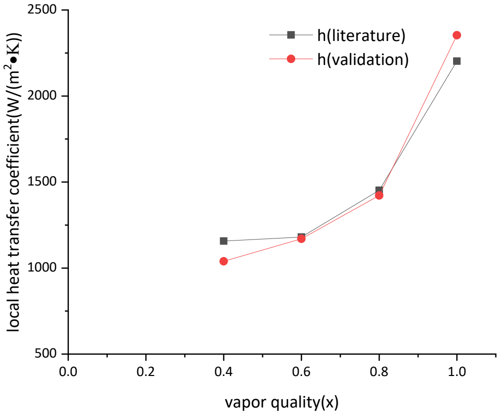


Fig.3 Effect of inlet vapor quality on local heat transfer coefficient

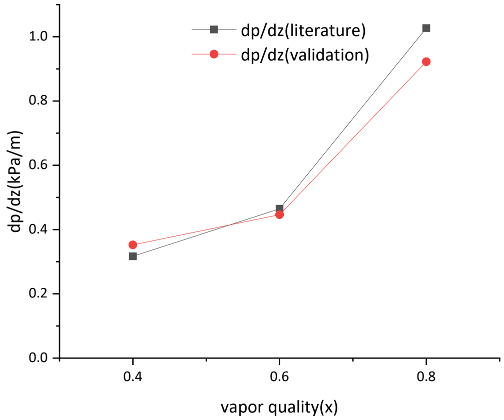
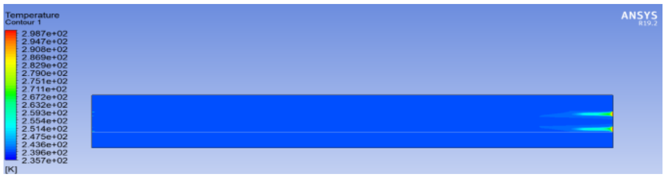


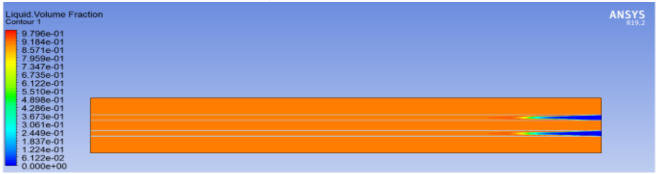
Fig.4 Variation of pressure drop with the inlet vapor quality

The first validation was performed at G=63.63kg/m2 •s and saturation temperature of 48.51°C. The results are shown in Fig.3 and 4. It can be seen that the validation results have a similar trend to those in the literature, and the error is small. This verification proves that condensation can be carried out under the evaporative condensation model in the fluent.

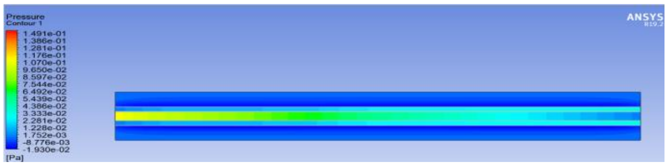
The second validation switched work medium from R134a to a mixture of CO_2 and O_2, and the physical model was changed from a two-stream heat exchanger to a three-stream heat exchanger. The following contours are named a, b and c, which are the temperature contours, liquid volume fraction contours and pressure contours respectively.



a. Temperature contours



b. Volume fraction contours



c. Pressure contours

Fig.5 Different contours at volume fractions of impurity gas=0.1

As show in Fig.5, We can see the corresponding distribution and variation trend of temperature, pressure and liquid volume fraction in the three contours. In the temperature contours, the hot fluid in the annular pipe is cooled by the two cold fluids and its temperature decreases. After the temperature drops to saturation temperature, the gas CO_2 condenses into liquid CO_2 and the gas in the pipe decreases. Therefore, in the volume fraction contours, the liquid volume fraction gradually increases along the length of the pipe, while the pressure decreases in the pressure cloud diagram.

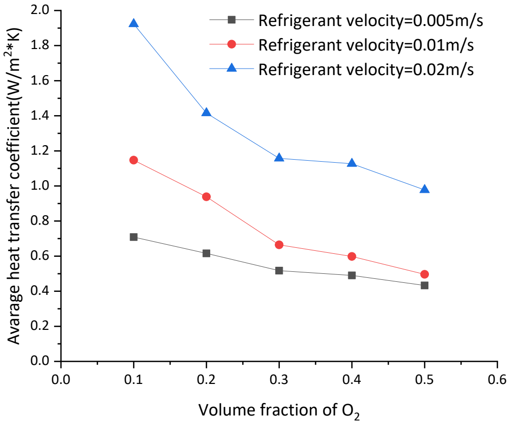


Fig.6 Variation of average heat transfer coefficient under different impurity gas volume fraction

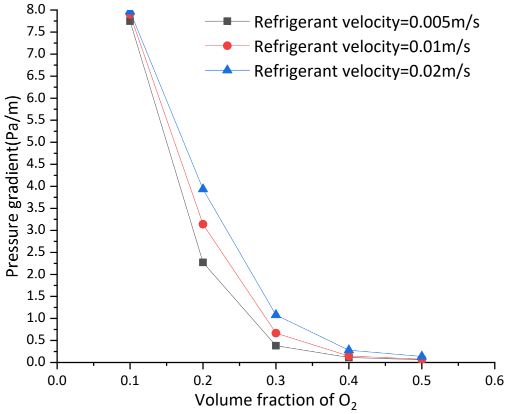


Fig.7 Variation of pressure drop under different impurity gas volume fraction

The variation of average heat transfer coefficient and pressure drop are showed in Fig.6 and 7. At the same refrigerant flow velocity, the average heat transfer coefficient decreases with the increase of impurity gas volume fraction. At the same impurity gas volume fraction, the average heat transfer coefficient increases with increasing refrigerant flow velocity. The average heat transfer coefficient decreases most sharply when the volume fraction ranges from 0.1 to 0.3, and the decline trend gradually flattens out in the following range. At the same refrigerant flow velocity, the downward trend of pressure drop in Fig.7 is the same as that in Fig.6. However, when increasing the refrigerant flow rate, the pressure change is not obvious. So far, the CO_2 condensation with impurity gas has been verified under the evaporative condensation model.

4. CONCLUSIONS

This work studies the influence of impurity gas(O2) on the performance of CO_2 condensation in the multi-stream heat exchanger. Two parameters under the different volume fractions of impurity gas(O_2) are compared based on the model of three-stream heat exchanger. Based on the results, the following conclusions are drawn:

•The evaporation and condensation model in FLUENT is verified, and the condensation in the heat exchanger meets the expectation under this model.

•The average heat transfer coefficient and friction pressure drop decrease with the increase of impurity gas(O_2) volume fraction.

•With the increase of refrigerant velocity, the average heat transfer coefficient and frictional pressure drop have the same increasing trend under the same impurity gas(O_2) volume fraction.

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