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Experimental investigation of steam condensation with high concentration CO_2 on a horizontal tube

Minghui Ge, Jun Zhao, Shixue Wang*

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- Investigation of steam condensation with high fractional CO_2.
- A drop of nearly 99% in heat transfer coefficient when the CO_2 concentration reaches 89.7%.
- Local condensation heat transfer characteristics on tube are analyzed.
- The new correlation can improve prediction uncertainty less than ±20%.

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ABSTRACT

An investigation was conducted for steam condensation with high fractional CO_2 on a horizontal tube. Condensation heat transfer characteristics were obtained with a steam mixture velocity of 0.21 m/s and CO_2 mass fraction of 11.2%–89.7%. The condensation heat transfer performance significantly deteriorated with the increase of the concentration of CO_2, decreased with the increase of surface sub-cooling and this influence decreased as the CO_2 mass fraction increased. Also, the variation amplitude of heat transfer coefficient decreased with the increase of CO_2 concentration. In addition, the correlation based on experimental data expanded its scope of application significantly compared with previous literature.

1. Introduction

Climate change caused by greenhouse gases has become a critical issue of worldwide concern. Among greenhouse gases, CO_2 accounts for a high proportion of the amount in the atmosphere, and is responsible for 70% of the global warming effect [1].Although renewable energy resources have been exploited, the world will remain largely dependent on fossil fuels for the next decades. In this case, CO_2 capture and storage (CCS) has been proposed as a sustainable technology to mitigate greenhouse gases by the Inter-governmental Panel on Climate Change (IPCC). CCS consists of a set of technological components associated with capturing, transporting and storing CO_2 deep underground. The capture of CO_2 includes post-combustion, pre-combustion and oxy-fuel combustion that contributes 75% to overall CCS costs [2]. To meet the burial requirement, the CO_2 must be separated and purified after capturing. Nowadays, the technologies of CO_2 separation mainly contain absorption, adsorption, cryogenics and membranes [3,4]. Among these technologies, chemical solvent absorption processes are considered to be the most feasible method. For the well developed amine absorption process (see Fig. 1 and Equation (1)), the vapor mixture must be condensed: the CO_2 must be purified for deep burial, and the steam back to the system to balance the concentration of amine solution [5]. And for the low-cost calcium-looping process (see Equation (2)), the researchers use steam to reduce the partial pressure of CO_2 and then decrease the calcination temperature. The gas mixture containing CO_2 and steam exits the reactor and must be further condensate for storage [6,7]. Therefore, the research of steam condensation heat transfer with high fractional CO_2 gas has important application value for CO_2 purification.

$$CO_2 + 2HOCH_2CH_2NH_2 \underset{\text{heat absorption}}{\overset{\text{heat release}}{\rightleftharpoons}} HOCH_2CH_2HNCOO^- + HOCH_2CH_2NH_3^+ \quad (1)$$

* Corresponding author. Tel./fax: +86 2227402567.
E-mail address: wangshixue_64@tju.edu.cn (S. Wang).

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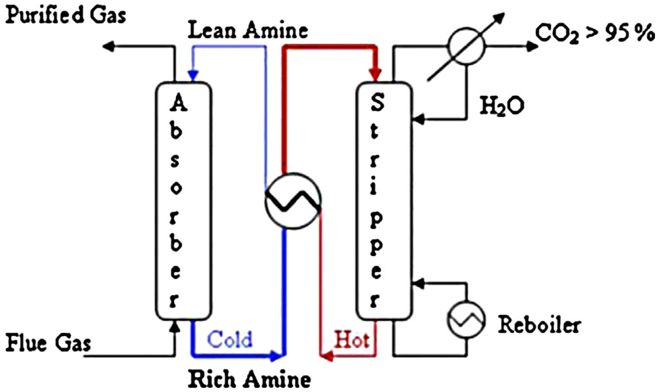

Fig. 1. Simplified CO_2 capture process.

$$CaO(s) + CO_2(g) \rightleftharpoons CaCO_3(s) \quad \Delta H_{25\,^\circ C} = \pm 178 \text{ kJ/mol} \tag{2}$$

The presence of a CO_2 component in gas–vapor mixtures is treated as non-condensable gas. The earliest experimental work on air/steam condensation dates back to 1929 when Othmer [8] measured heat transfer rates for a 7.62 cm diameter by 1.22 m long copper tube placed in a stagnant air/steam environment. The results showed that the presence of a small amount of non-condensable gas in vapor can reduce the condensation rate significantly. An empirical correlation was derived relating the heat transfer coefficient to the air/steam volume ratio and to the temperature difference between the cooled surface and the air/steam mixture, i.e.,

$$\log h_0 = (1.213 - 0.00242T_g)\cdot\log\Delta T + (\log\Delta T/3.439 - 1)\cdot [\log(X_a + 0.505) - 1.551 - 0.009T_g], \quad X_a = 0\sim0.06 \tag{3}$$

where T_g is the temperature of the gas–vapor mixture. ΔT is surface sub-cooling. X_a is mole fraction and h_0 is the heat transfer coefficient of vapor mixture.

For the condensation on a flat plate, Al-Diwani and Rose [9] conducted condensation experiments of steam on a 97 × 97 mm vertical plate surface in the presence of air, argon, neon and helium under free-convection conditions. The NCC mass fraction is 0–25% and the surface sub-cooling is 5–80 °C. The heat transfer coefficient increased with increasing total pressure, but the effect of surface sub-cooling and chamber height was not obvious. Desesquelles and Foch [10] conducted experiments and numerical simulations of heat and mass transfer in an incompressible boundary layer with condensation over a flat plate. The air–steam flow at atmospheric pressure is saturated. The numerical results are in good agreement with experiments for laminar and turbulent boundary layers. Huhtiniemi and Corradini [11] investigated the effect of surface orientation on the condensation of a steam–air mixture. The orientation of the condensing surface was varied from 0 to 90°, with a variable air–steam mass fraction of 0–87%. By tilting the condensing surface from horizontal to vertical position, the heat transfer coefficient decreased 15–25% depending on the mass fraction. Wei [12] studied the laminar film condensation heat transfer of R113-air (0–2.6%) mixture on a vertical surface of 50 × 50 mm. The heat transfer coefficient was measured in addition to making visual observation of the condensation process.

Ivashchenco et al. [13] measured the overall heat transfer coefficient of a vapor–nitrogen (0–8%) mixture on a vertical tube at about 0.8 MPa total pressure. The authors observed that the heat transfer coefficient decreases most drastically with a change in the volumetric gas content from 0 to 5%, whereas in the range of 6–8% the decrease was much smaller. Bohdal [14] performed an experimental study of the process of the refrigeration medium R404A in a tubular channel in the presence of air. The results confirm the negative effect of the air present in the condenser on the process of condensation of the refrigeration medium, which leads to a decrease of the heat transfer coefficient, enlargement of the condensation zone, and an increased flow resistance in the multi-phase, multi-component flow system. It is found that a 2.5% air volume content decreases the heat transfer coefficient by 20–50% with an increase of pressure drop by as much as 30% with respect to condensation of pure refrigeration. Hasanein [15] studied the condensation in a steam/helium system and steam/air/helium system in a 0.046 m I.D. vertical tube, and obtained the following correlations based on mass fraction of NCC:

$$Nu = 1.279Re^{0.256}W_h^{-0.741}Ja^{-0.952} \tag{4}$$

$$Nu = 0.12Re^{0.368}W_a^{-0.554}W_h^{-0.676}Ja^{-0.931} \tag{5}$$

The above expressions are appropriate for a steam/helium system and steam/air/helium system respectively. Re and Ja are the respective vapor mixture numbers of Reynolds and Jacob.

$$Ja = C_{p,\mathrm{mix}}\cdot(T_{sat} - T_i)/L_h \tag{6}$$

Vierow and Schrock [16] conducted an experimental study using a 22 mm ID vertical tube, natural circulation air/steam system. They obtained the local heat transfer coefficient as a function of decay factor f:

$$f = h_{exp}/h_{Nu} = f_1f_2 = (1 + Re_m^a)\left(1 - m_g^b\right) \tag{7}$$

Where h_{exp}, h_{Nu} are the heat transfer coefficient measured by experiment and calculated by Nusselt theory for pure vapor. The undetermined parameters of a and b can be determined by different experimental data. Siddique et al. [17] dealt with the problem of air/steam and helium/steam flowing downward in a vertical tube. The condenser tube is a 50.8 mm O.D, 46.0 mm I.D, and 2.54 m effective length stainless steel tube, surrounded with a 62.7 mm inside diameter stainless steel concentric jacket pipe. For the air/steam experiments the inlet air mass fraction was 10–35%. For the helium/steam mixture the helium mass fraction was 2–10%. The data from the experiments were correlated by relationship of the form:

$$\text{For air/steam mixture}: Nu_x = h_xd/k = 6.123Re_m^{0.223}\left((M_{a,w} - M_{a,b})/M_{a,w}\right)^{1.144}Ja^{-1.253},\ 0.1 < M_{a,w} < 0.95, 445 < Re_m < 22700,\ 0.004 < Ja < 0.07 \tag{8}$$