Numerical Study of Condensation Heat Exchanger Design in a Subcooled Pool: Correlation Investigation

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1. Introduction

Generally the condensation heat exchanger has higher heat transfer coefficient compared to the single-phase heat exchanger, so has been widely applied to the cooling systems of energy plant. Recently vertical or horizontal type condensation heat exchangers are being studied for the application to secondary passive cooling system of nuclear plants. Lee and Lee [1] investigated the existing condensation correlation to the experiment for heat exchanger in saturated pool. They concluded Traviss' correlation showed most satisfactory results for the heat transfer coefficient and mass flow rate in a saturated water pool. In this study, a thermal sizing program of vertical condensation heat exchanger to design, TSCON(Thermal Sizing of CONdenser) was validated with the existing experimental data of condensation heat exchanger in a subcooled pool for pure steam condensation.

2. Numerical study

2.1 TSCON

TSCON solves one-dimensional steady continuity, momentum and energy equations together by nodalizing a pipe. After assuming initial local heat load, condensation part of the pipe length and mass flow rate are decided. Total pressure is assumed to be constant through the pipe. Inner wall temperature of the pipe at each node is calculated by the given condensation heat transfer coefficient. Outer wall temperature of the pipe is calculated by one dimensional pipe conduction equation. Calculated pipe length by the outside pool boiling heat transfer coefficient is compared to the original. If it was not same, the inner wall temperature would be iterated. The original heat load up to satisfy overall heat transfer rate is also iterated. Then, the same procedure applies to single phase part of the pipe. Inside the pipe heat transfer coefficient, the existing condensation correlation, discussed in next subsection, is used for condensation section and the Dittus-Boelter for single phase. Outside the pipe, natural convection correlation is adopted for the subcooled water pool.

2.2 Existing condensation correlations

Shah [2] reviewed the existing condensation heat transfer correlation. Since most correlations proposed for horizontal tubes, no well-validated correlation for vertical tubes was found. Soliman (1968) and Shah's correlation (1979) was stated to be vertical tubes typically. Gravitational liquid film effect cannot be negligible, so that a condensation correlation in a vertical tube is appropriate to be selected. Recently Thome (2003) reported a condensation correlation, but Thome's correlation was ignored in this study since they proposed it based on refrigerant as a working fluid. Six existing condensation correlations were chosen to validate TSCON: Akers (1959), Soliman (1968), Traviss (1973), Shah (1979), Blangetti (1982) and the improved Shah (2009) [2].

2.3 Experimental data set

From the decade, there have been a number of papers that study condensation heat exchanger design. Henderson et. al. [3] reviewed that most of these researches use forced convection for the heat removal with the presence of noncondensable gas. To investigate the existing condensation correlations in TSCON, the experimental data obtained at condensation heat exchanger without the presence of noncondensable gas in a subcooled pool is needed. Currently, one data set is available for the heat exchanger for pure steam condensation in a subcooled pool: Kim [4]. Kim provided 984 data points in Appendix B of the dissertation, but 275 data points are only appropriate to evaluate TSCON.

3. Results

Figure 1 shows the prediction of the correlations of condensation heat transfer coefficient with the experimental data of Kim [4]. Most of the condensation correlations under-predicted the experimental data except Soliman and Blangetti's correlations. Therefore, pure steam bulk flow is fully condensed inside the pipe for the case of some data using Soliman and Blangetti due to very high calculated condensation heat transfer coefficient, while still remaining at the exit of the pipe using others. Table I indicates both MAE (Mean Average Error) and MR (Mean Ratio), defined in Eqs. (1) and (2), of condensation heat transfer coefficient experimental data compared with six selected correlations.

The improved Shah's correlation gives the best prediction of the condensation heat transfer coefficient experimental data of Kim [4] with 32.9% MAE and

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|Exp_i - Cal_i\right|}{Exp_i}\times 100\ (\%) \qquad (1)$$

$$MR = \frac{1}{N}\sum_{i=1}^{N}\frac{Cal_i}{Exp_i} \qquad (2)$$

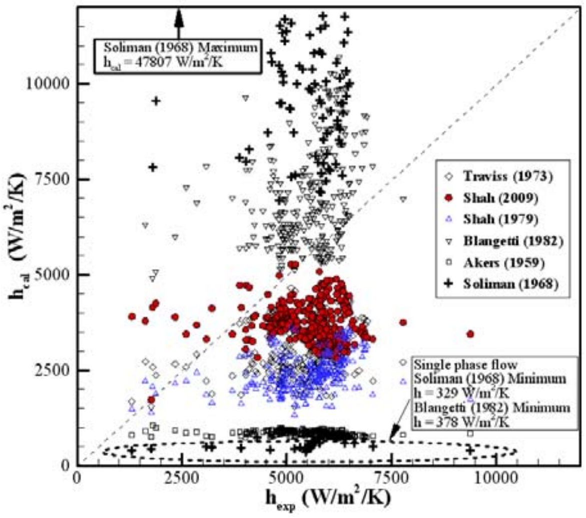

Fig. 1. The prediction of the correlations of condensation heat transfer coefficient with the experimental data of Kim [1]

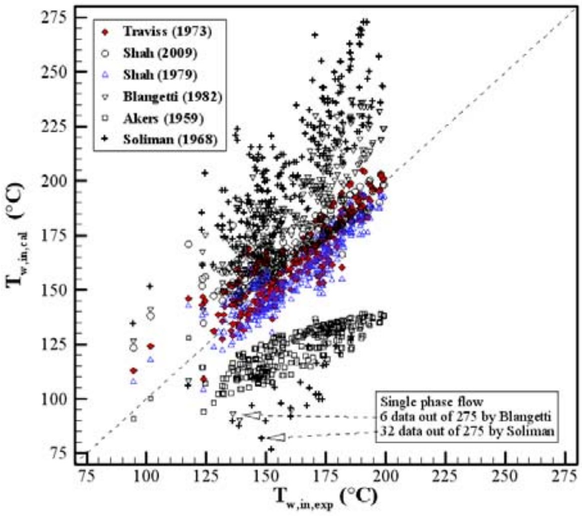

Fig. 2. The prediction of the inner wall temperature with the experimental data of Kim [1]

Table I: Mean average error (MAE) (%) and mean ratio (MR) of condensation heat transfer coefficient experimental data compared with the existing correlations

	Akers (1959)	Solima -n (1968)	Traviss (1973)	Shah (1979)	Blange -tti (1982)	Shah (2009)
MAE	83.6	221.7	44.5	54.4	34.6	**32.9**
MR	6.5	3.0	0.57	0.46	1.29	**0.73**

Table II: Mean average error (MAE) (%) and mean ratio (MR) of condensation mass flow rate experimental data compared with the existing correlations

	Akers (1959)	Solima -n (1968)	Traviss (1973)	Shah (1979)	Blange -tti (1982)	Shah (2009)
MAE	70.6	81.3	65.5	**65.2**	75.3	69
MR	1.63	0.92	1.2	1.31	**0.99**	**1.09**

0.73 MR. Lee and Lee [1] concluded Traviss' correlation showed most satisfactory results for the heat transfer coefficient and mass flow rate of the experimental data of Kim [4] in a saturated water pool. However, Traviss' correlation is even worse than Shah (1979), Blangetti (1982), and the improved Shah (2009) for the subcooled water pool.

Figure 2 is the prediction of the correlations of inner wall temperature with the experimental data of Kim [4]. Interestingly, Traviss (1973), Shah (1979), and the improved Shah's correlations (2009) predicted the measured inner wall temperature within the average error of 4.2%, 5.5%, and 5.9%, respectively, although condensation heat transfer coefficient predicted by the improved Shah's correlations is the best predictor.

Table II indicates both MAE (Mean Average Error) and MR (Mean Ratio) of condensation mass flow rate experimental data compared with six selected correlations. Based on average ratio of error, Blangetti (1982) and the improved Shah's correlation (2009) are closed to the value of unity. Using Soliman and Blangetti's correlations, however, single phase mass flow (no condensation mass flow) occurs at 32 and 6 data point out of 275 data points, respectively. Therefore, the average ratio of condensation mass flow rate is not correct. Except these correlations, the improved Shah's correlation gives the best prediction with 69% MAE and 1.09 MR as well as the condensation heat transfer coefficient.

4. Conclusions

From the investigation of the existing condensation heat transfer correlation to the Kim's experimental data, it is proposed that the improved Shah's correlation (2009) should be used to conduct thermal sizing design of condensation heat exchanger in a subcooled water pool without the presence of noncondensable gas.

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