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Numerical analysis of a heat exchanger used in a vapour absorption refrigeration system

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A B S T R A C T

Applications of falling film evaporators are in a wide range of industries, ranging from chemical industries, petroleum refinery, desalination and food process industries. This paper is focused on numerical and experimental investigation of vapour generator (falling film heat exchanger) of a vapour absorption refrigeration (VAR) system. The impact of key operating parameters like mass flow rate of fluid, inlet temperature and the concentration of the thermic fluid as well as the coolant, are experimentally studied and are compared with the numerical results. The deviation between the experimental and numerical results was found to be 8.72%, with a lesser deviation at lower temperatures. The min. percentage error is 2.15%, for a thermic fluid temperature at 50º C. There is a stronger agreement in the results for lower values of the glycol water mixture inlet temperature, than at high temperatures. A maximum of 1000 W/m2 heat is transferred to the aqua-ammonia with ammonia concentration of 0.6 by volume is observed for thermic fluid inlet temperatures of 80C. The effect of various operating parameters was numerically studied and interpreted.

Keywords:
Falling film evaporator
Vapour absorption refrigeration
Heat transfer
Generator
Absorber

1. Introduction

The compactness of any heat transfer device depends on its performance at optimum conditions. The present study focused on the performance evaluation of a horizontal falling film heat exchanger used for refrigerant vapour generation in Vapour Absorption

*Abbreviations and Symbols:*CFC, Chlorofluorocarbon; HCFC, Hydrofluorocarbon; LPH, Litre per hour; VARS, Vapour Absorption Refrigeration System; F, correction factor; D*T*, temperature difference between heat transfer fluids; D_i, D_o, inner and outer diameters of the heat exchanger tubes; h_i, h_o, inner and outer heat transfer coefficients; k, heat exchanger tube material thermal conductivity; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number.

Refrigeration (VAR) system is considered. Srikhirin et al[.15] car- ried out a detailed review on vapour absorption cooling systems. Vapour absorption cooling system is same as vapour compression cooling systems in principle. However, the vapour compression cooling systems requires electrical energy as the input drive the compressor for refrigerant vapour compression whereas in vapour absorption refrigeration system it requires heat energy to separate vapour from the refrigerant. Vapour Compression Refrigeration (VCR) systems requires huge quantities of high grade electrical energy to compress the vapour refrigerant exiting evaporator to the condenser section of the VCR system. VAR systems requires less quantity of high grade electrical energy to drive the pump and utilizes more quantity of low grade energy heat. However it requires huge quantities of heat energy in vapour generator to sep- arate refrigerant vapour from the liquid absorbent. Vapour absorption and generation takes place in two separate heat exchangers and hence the size of the VARS system is bulky and will have higher cost compare to VCR system. These systems will not use chlorofluorocarbons and hydro chlorofluorocarbons and hence the depletion of Ozone layer can be avoided.

A low temperature thermal power plant utilizing low grade heat is designed and optimized by Ganesh and Srinivas[7]. They used aqua ammonia as the working fluid and ammonia vapour is generated in a vapour generator using any low grade energy and is expanded in an expander. The performance of the plant is studied for different operating temperatures of vapour generator and the best suitable range of temperature is proposed. A new method of generating shaft power and cooling simultaneously using aqua ammonia mixture utilizing solar energy is proposed by Shankar and Srinivas [14]. They optimized the operating process parameters for maximum generation of vapour in the vapour generator and the expansion of vapour in expander and refrigerant vapour quantity for maximum cooling for maximum utilization of energy. Chiranjeevi and Srinivas[4] carried out simulation studies on the impact of vapour absorption refrigeration system on the performance of integrated humidification dehumidification desalination and cooling system. They observed maximum energy utilization with ammonia concentration of 47% with a generator temperature range of 100–110°C. Chiranjeevi and Srinivas[5] further studied the possibility of integration of VAR system with a single and two stage Humidification Dehumidification (HDH) desalination system and compared the performance results with HDH desalination without VAR cooling. Theoretical studies recommended that a two stage HDH desalination with normal cooling water cooling in first stage and VAR generated chilled water cooling in the second stage highest desalination yield, cooling output and the energy utilization factor (EUF). Maximum desalination water obtained was 2.5 L per hour, and 200 W cooling energy generation and the EUF obtained was in the range of 0.18–0.33.

The performance evaluation of horizontal tube falling film evaporator was performed experimentally by Yoon et al[.17]. They performed experiments on evaporator with different diameter tubes and observed that the performance of the evaporator increases with decrease in tube diameter. The results obtained for overall heat transfer coefficients are compared with the literature for validation. Yang and Wang[16] carried out numerical studies to evaluate the heat transfer performance of falling film evaporators having different geometry of tube bundles, which was used in a large scale vapor compression cooling system. The simulated flat tube geometry results and experimental results are compared and validated the simulation model. The authors concluded that the results obtained are useful for falling film evaporator design under realistic conditions.

Spray/falling film evaporators extensively used in Ocean Thermal Energy Conversion (OTEC), thermal desalination process and petroleum industries. Falling film heat exchangers are rarely used in heat pumps and refrigerators, but these are very good substitute for pool boiling evaporators because of their prospective benefits in reducing the refrigerant charge and enhanced heat transfer characteristics [6]. Indirect contact heat exchangers have numerous number of applications for transfer heat from one fluid to the other fluid in wide range industries. Vapour generator is an indirect contact heat exchanger which one of the most critical component in absorption refrigeration system[20]. Aprea et al. [1] carried out experiments on Lithium Bromide (LiBr) – water vapour absorption refrigeration machine and revealed that LiBr-water solution flow rate is 2 –5 times higher than the simulated value. Areaklioglu et al. [2] investigated to improve the absorption process by removing heat from the liquid film spread on set of cooled rotating discs simultaneously. This design requires huge flow rates of liquid mixture and they observed that the heat absorption rate of rotating discs is much higher than the conventional design for given surface area of the discs and hence less absorber size.

The horizontal tube falling film evaporators have a clear advantage over the flooded tube bundles due to evenly distributed thin film over the surface of the tubes. This results in very high overall heat transfer coefficients in the range of 500–1000 W/m²K. High heat transfer rates will help in minimizing the evaporator size and hence reduces the required cost and space. Various experimental investigations have been carried out with falling film heat exchangers using LiBr-water mixture as the working fluid pair. Kyung et al. [12] and Islam [10] developed thermodynamics simulation models and validated the model with experimental results. Their main focus is to study the vapour absorption refrigeration with LiBr-water absorbent-refrigerant fluid pair. Kalogirou et al. [11] have designed and constructed a LiBr–water vapour absorption refrigerator with cooling capacity of 1 kW and detailed design of each and every component of the systems described. Prost et al. [13] carried out numerical studies on a single effect evaporator used as a generator in VAR system and determined the heat transfer coefficients. They extrapolate these results to multiple effect VAR system by varying various operating parameters. They developed correlations for heat transfer coefficients from the simulated data generated. Harikrishnan et al. [9] developed a numerical model for falling film evaporator with horizontal absorber tubes to study fluid flow and the heat and mass transfer characteristics by using a two dimensional technique. Giannetti et al[8] carried out analytical studies on partially wetted horizontal falling film heat exchanger to estimate the heat and mass transfer coefficients. The studies reveal that lower Reynolds number in partially wetted conditions results in higher heat transfer rates. Zhao et al.[19] studied the heat transfer characteristics numerically on a falling film horizontal tube in subcooled state. They developed correlations and shown that about 92% of predicted is within a deviation of ±10% and it predicts 78% of the data available in literature with a deviation range of ±30%. Bohra et al.[3] carried out experiments to develop heat and mass transfer models for ammonia-water absorber falling film horizontal tubes by varying the operating conditions. They developed correlations for vapour phase mass transfer, liquid phase mass transfer and local liquid phase mass transfer coefficients were developed and verified that these correlations can predict the data within a deviation of ±25%. Zhang et al. [18] carried out numerical and experimental studies on heat and mass transfer characteristics of a Lithium Bromide water horizontal tube absorber. They carried out studies on falling film, liquid column and falling droplet of water in the absorber of the VAR system. The studies conclude that the vapour absorption rate of condensed droplet can reach up to 50% by increasing the flow rate of the solution coming from generator of VAR.

However, the above studies fall short in being unable to computationally validate the heat transfer correlations, which gives a better understanding of the actual flow dynamics in the system. Also, the numerical approach is a much more complex and time consuming process.

2. Methodology

There are two methods to analyse the performance of the heat exchanger. The first is by performing experiments, and the second is through numerical simulation. Present study aims to compare the two results obtained from the model and experiments and thus validate the heat transfer correlations. The falling film heat exchanger is selected in VAR system due to its compactness when compared with a shell and tube heat exchanger.

The heat and mass transfer phenomena in falling film heat exchangers takes place between a surfaces that emits r absorbs heat and a thin liquid film. Gravity will help the liquid to fall or flow over hot surface and these falling films will obtain high heat transfer rates and this method is commonly used for heating or cooling applications in process industries. Recently these heat exchangers are largely used in heat pumps and VAR systems. The line diagram of the falling film vapour generator is shown in the Fig. 1 with the representation of different fluids entry and exit.

Fig. 2 represents the photograph of the experimental setup developed with necessary instrumentation. Ammonia-Water mixture is used as the refrigerant absorbent pair in VAR with vapour generator as a horizontal falling film heat exchanger. VAR is a part of a trigeneration plant in which ethylene glycol was used as the thermic fluid for transferring heat from solar collectors and the same is used as the heat transfer medium in vapour generator of VAR. The photograph shown inFig. 3 is an assembled falling film vapour generator with necessary instrumentation. The shell of generator is made of Stainless Steel (SS) with Stainless Steel tubes arranged in a triangular pitch in the shell. Two SS tubes are joined with a common header to spray strong solution is placed above the tube bundle with thermic fluid circulation. The thermic fluid is 30% glycol water flows at a rate of 100 LPH (0.02689 kg/s) inside the tubes of heat exchanger. VAR working fluid aqua ammonia is sprayed from the top on to the tube bundle at 18 LPH (0.00408 kg/s) mass flow rate, and is sprayed onto the hot tubes. This thus separates the NH_3– water mixture into liquid and vapour. The liquid, is collected at the bottom the exchanger, whereas the vapour, is collected at the top of the exchanger and is sent to a condenser. The thermic fluid is circulated through the tubes at 4 bar and the strong solution is pumped to 13 bar pressure and sprayed on the top of tube bundle.

The temperatures of thermic fluid and aqua-ammonia are measured by keeping thermos couples at inlet and outlet section of the pipes connecting heat exchanger and mass flow rates are measured with calibrated rota meters. The thermic fluid supplied to generator will provide sensible heat to rise the aqua-ammonia to saturation state and the latent heat vapourise the refrigerant ammonia by separating from water. In heat exchangers the temperature difference (DT) between the heat exchange fluids is not constant from entry to the exit and it varies along the length of the heat exchanger. So, in heat transfer analysis mean temperature difference (DT_m) is established between the heat exchange fluids. The heat duty of heat exchanger (Q) can be estimated by using Eq(.1).

$$Q = UADT_m \quad (1)$$

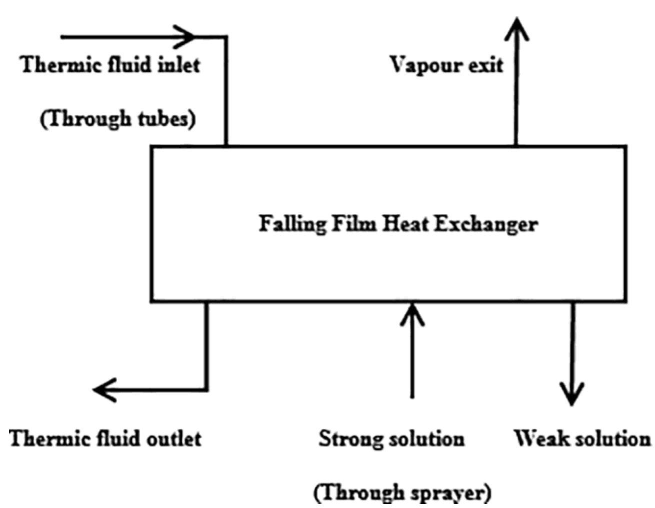

Fig. 1. Falling film heat exchanger line diagram indicating fluid interactions.

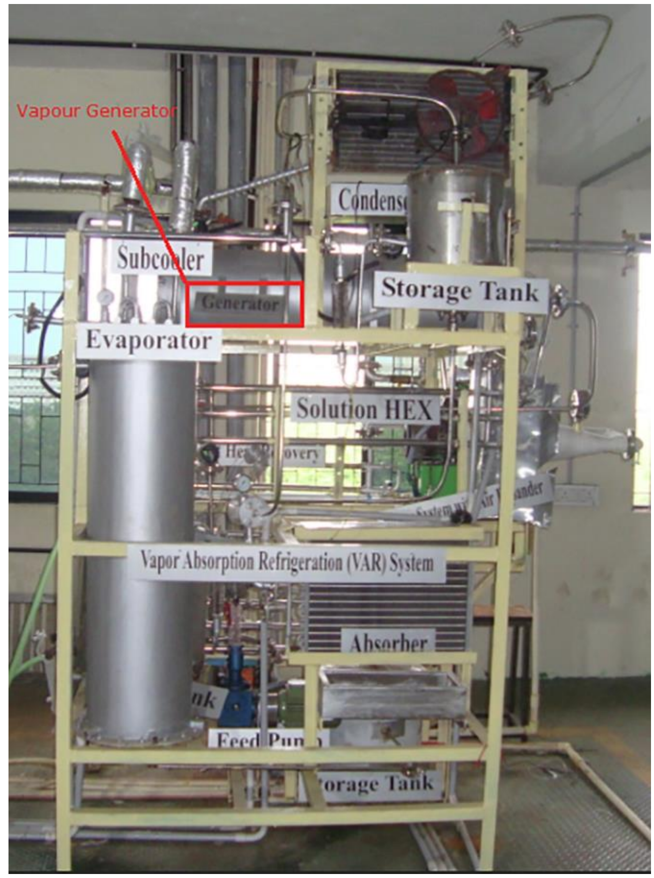

Fig. 2. Experimental setup of Vapour Absorption Refrigeration system.

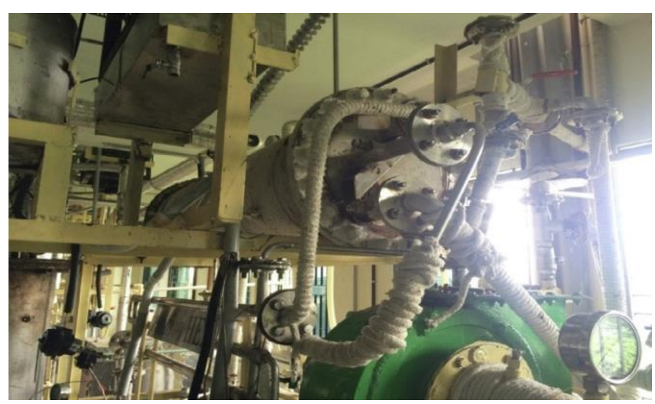

Fig. 3. Experimental setup of horizontal falling film vapour generator in Vapour Absorption Refrigeration System.

where DT_m and U are found from the following equations.

$$DT_m = F DT_{ln} = F(DT_i - DT_o)/\ln(DT_i/DT_o) \quad (2)$$

$$U_i = \frac{1}{\frac{1}{h_i} + F_i + \frac{1}{2k} D_i \ln\frac{D_o}{D_i} + \frac{D_i}{D_o} F_o + \frac{D_i}{D_o}\frac{1}{h_o}} \quad (3)$$

When the fluid flows inside a smooth tube with turbulent conditions, the Nusselt number can be found by the following expression.

$$Nu = \frac{(f/8)Re_D Pr}{K_1 + K_2 (f/8)^{1/2} (Pr^{2/3} - 1)} \quad (4)$$

where f, K_1 and K_2 are determined from the following equations.

$$f = 1/\left[(1.82 \times \log_{10} \times Re_D - 1.64)\right]^2 \quad (5)$$

$$K_1 = 1 + [3.4 \times f] \quad (6)$$

$$K_2 = 11.7 + 1.8/Pr^{1/3} \quad (7)$$

Using the mentioned equations, a simulation code is developed using MATLAB in order to get the outlet temperature of the thermic fluid and the temperature of the ammonia water mixture at the exit of heat exchanger for set of measured temperature and mass flow rate at inlet. The influence of the operating parameters (inlet temperature, fluid flow rate and the concentration), on the outlet temperature, is also studied by using the simulation model developed.

3. Results and discussion

Experiments were conducted using thermic fluid as 30% glycol water mixture at a flow rate of 100 LPH and aqua-ammonia of 28% ammonia concentration is used for the experiment with a flow rate of 18 LPH. Table 1 summarizes the variation of glycol water mixture outlet temperature and the generator pressure with rise in the glycol water mixture inlet temperature.

Variation of glycol water mixture temperature at heat exchanger outlet with increase in its inlet temperature is shown in Fig. 4. The thermic fluid entry temperature is varied from 26°C to 90 °C, for which the outlet temperature of the fluid was vary between 26 and 86°C, with a rise in pressure up to 6 bar. From Fig. 4 it can be observed that as the entry temperature of thermic fluid increases, the exit temperature of the glycol water mixture increases linearly. However, during the heat exchange process, the thermic fluid transfers some of its heat to the working fluid, and thus reduces in temperature as it comes out of the heat exchanger. Thus, for an inlet temperature of 50°C, the thermic fluid outlet temperature is 46°C. On an average, there is a 4–5°C drop in the thermic fluid outlet temperature as compared to the entry temperature.

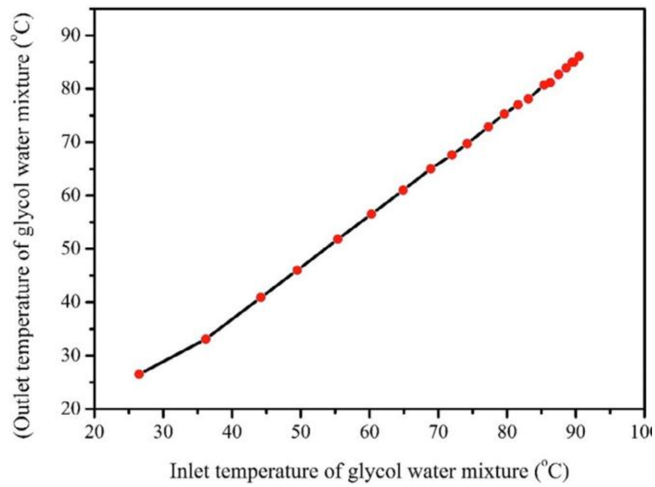

Fig. 4. Experimental observation of variation of glycol water outlet temperature with its inlet temperature.

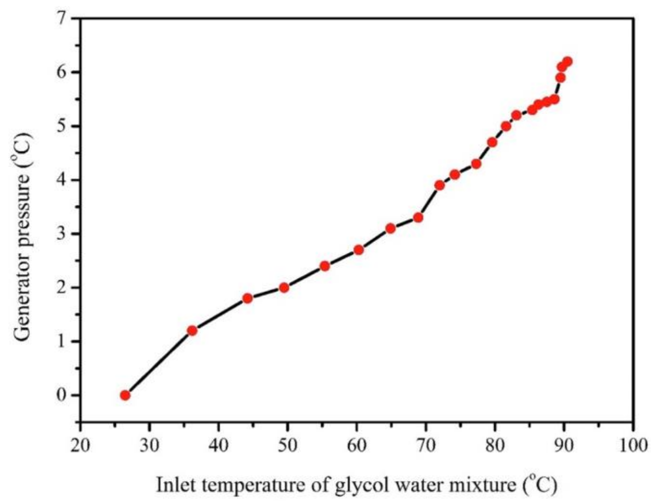

Fig. 5. Experimental observation of variation of generator pressure with glycol water inlet temperature.

Table 1
Experimental observations with variation of thermic fluid inlet temperature.

Entry temperature (°C)	Exit temperature (°C)	Generator pressure (bar)
26.5	26.5	0.0
36.2	33.1	1.2
44.2	40.9	1.8
49.5	46.0	2.0
55.4	51.8	2.4
60.3	56.5	2.7
64.9	61.0	3.1
68.9	65.0	3.3
72.0	67.6	3.9
74.2	69.7	4.1
77.3	72.9	4.3
79.6	75.3	4.7
81.6	77.0	5.0
83.1	78.1	5.2
85.4	80.7	5.3
86.3	81.2	5.4
87.5	82.7	5.45
88.6	83.9	5.5
89.5	85.0	5.9
89.7	85.0	6.1
90.5	86.1	6.2

Table 2
Deviation of thermic fluid inlet temperature between experimental reading and numerical simulation result.

Experimental result	Numerical result	%Deviation
26.5	26.7	0.749
33.1	34.2	3.216
40.9	40.8	0.245
46	45.4	1.321
51.8	49.7	4.225
56.5	55.2	2.355
61	58.7	3.918
65	62.7	3.668
67.6	63.8	5.956
69.7	66.4	4.969
72.9	68.7	6.113
75.3	69.2	8.815
77	71.2	8.146
78.1	72.3	8.022
80.7	73.8	9.349
81.2	75.3	7.835
82.7	76.2	8.530
83.9	76.8	9.244
85	77.4	9.819
85	78.2	8.695
86.1	79.4	8.438

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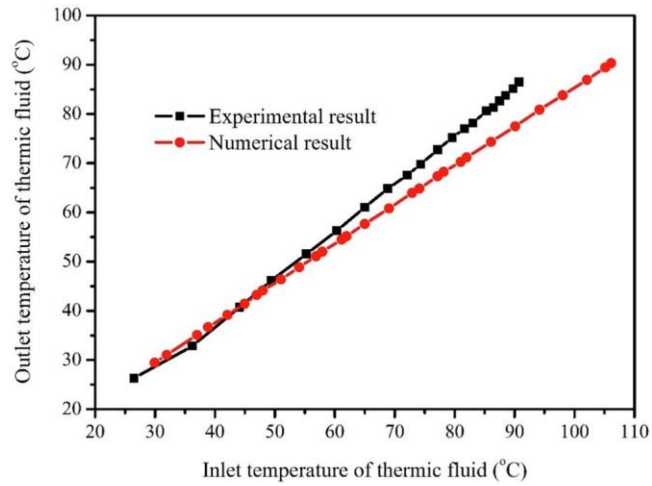

Fig. 6. Numerical validation of experimental results for ammonia concentration of 28%.

Variation of vapour pressure in the generator with glycol water mixture temperature is shown in Fig. 5. From the figure it is observed that the generator pressure increases with an increase in inlet temperature of the thermic fluid and the pressure is increase as a linear function.

An analytical model is developed using MATLAB to study the effect of different operating parameters on the heat exchange process. The solution was fed through the inlet of the horizontal spray tubes of the vapour generator is termed as the strong solution. Whereas, the solution that is collected at the exit of the generator is known as the weak solution. Concentrations of the weak and strong solutions, vapor concentration, outlet temperature of the fluid, and the generator pressure are inter-dependent quantities, and thus the effect of varying one of the parameters, on the outlet temperature or pressure, are studied. The cold and hot fluid outlet temperature values are estimated for fixed inlet conditions i.e. constant values of inlet temperature, mass flow rate and concentrations are predicted from the numerical model and compared them with experimental results.

The experimental observations of glycol water mixture outlet temperature and its predicted values with the simulation model are tabulated in theTable 2. The Fig. 6 compares the experimental observations of outlet temperature of glycol water mixture with the simulated ones. It can be observed from theFig. 6 that there is a close correlation between the experimentally and numerically obtained results. At the operating temperature of the generator i.e. 80 °C, the maximum error percentage is found to be an acceptable value of 8.72%. The minimum percentage error is 2.15%, for a thermic fluid temperature of 50°C. There is a strong agreement in the results for lower values of thermic fluid inlet temperature than at higher temperatures.

Fig. 7 reveals the variation of outlet temperatures of both heat exchange fluids from the falling film vapour generator with respect

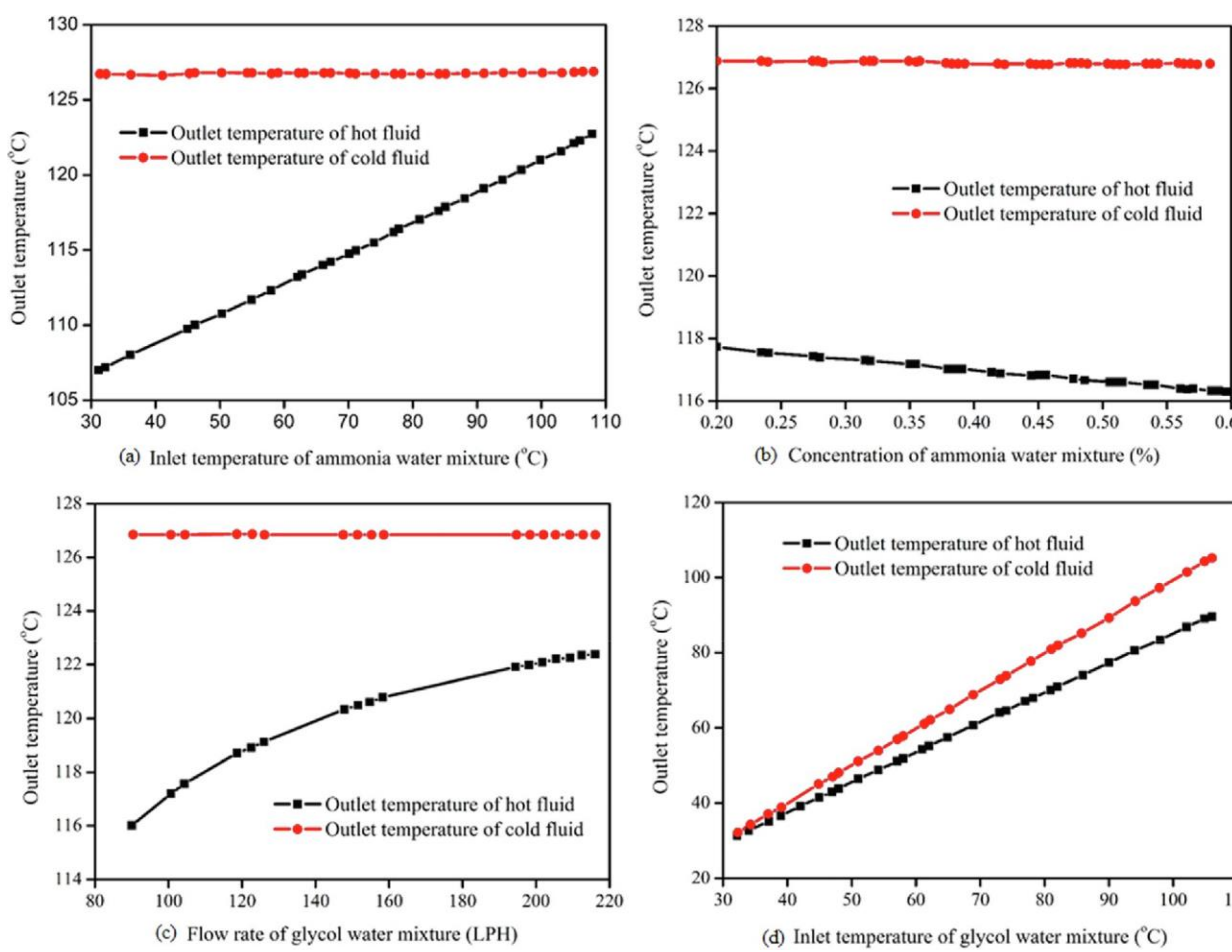

Fig. 7. Variation of outlet temperature of hot and cold fluid with change in inlet parameters.

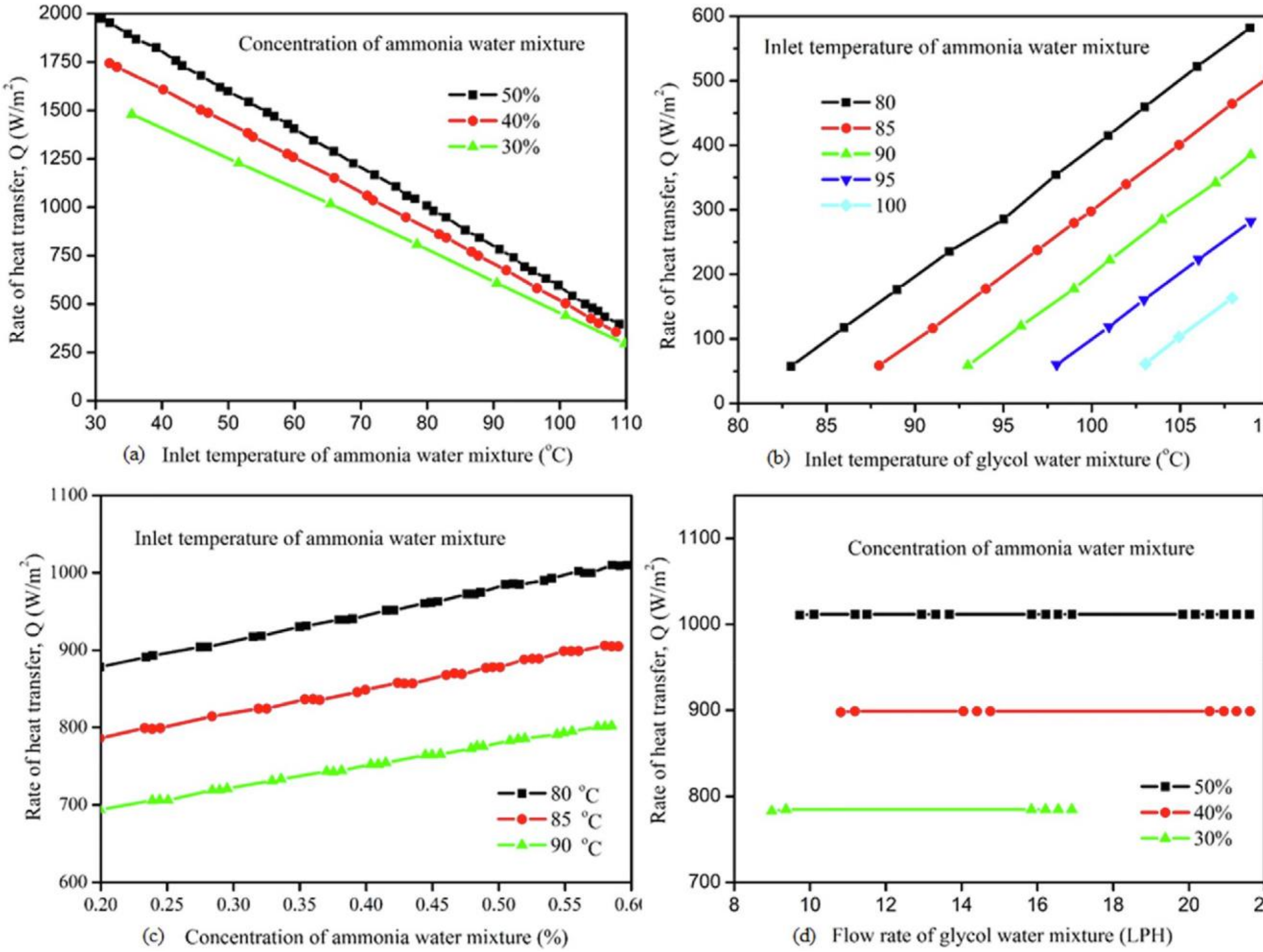

Fig. 8. Influence of change in inlet parameters on the rate of heat transfer.

to change in the ammonia water mixture inlet temperature and its concentration and glycol water temperature and its flow rate. The influence of the ammonia water mixture inlet temperature to the vapour generator on the outlet temperatures of both ammonia water and thermic fluids is shown inFig. 7(d). The inlet temperature of the ammonia water mixture has been varied from 35 to 110 °C. It is observed that the exiting temperature of the glycol water mixture, rises with an increase in ammonia-water mixture temperature at inlet. However, at the outlet the temperature of ammonia-water mixture does not show much dependency on the inlet temperature of ammonia-water mixture, but depends on the temperature of glycol–water mixture instead as shown in figure Fig. 7(c). The Fig. 7(d) reveals that the heat load required for the effective operation of the generator, decreases as the inlet temperature of the ammonia water mixture increases. It is because, the temperature difference becomes lesser for higher temperatures of the cold fluid.

The influence of glycol water mixture inlet temperature on the outlet temperatures of hot and cold fluids is shown inFig. 7(a). The glycol water mixture temperature at the generator inlet is varied from 30 to 110°C. It is observed that the outlet temperature of the glycol water mixture, as well as aqua-ammonia mixture increases with increase in the glycol water mixture temperature at the generator inlet. There is a parallel correlation between the outlet temperatures of both the fluids, with respect to the variation in hot fluid temperature at the inlet. The rate of heat transfer also increases linearly with increase in the exiting temperature of the thermic fluid. In order to study the heat exchange rate between the fluids the temperatures of both the fluids at inlet are varied. It is observed that the range of the heat duty values decreases with increasing the inlet temperature of the thermic fluid is shown in Fig. 8(b). This is because the temperature of the hot fluid has to be greater than or equal to the inlet temperature of the cold fluid at that point, for effective operation.

The influence of aqua-ammonia concentration for a range of 20–60% on the outlet temperatures of hot cold fluid are shown in Fig. 7(b). It is observed that the outlet temperatures of glycol water mixture, does not vary significantly with variation in the concentration of the ammonia water mixture at the inlet. There is slight decrease in the values of the outlet temperature of the ammonia water mixture, as the concentration of the cold fluid increases. However, the heat transfer rate increases with increase in the concentration of ammonia in the mixture as shown inFig. 8(c). The increase in temperature difference between the hot and cold fluids increases with an increase in the concentration of ammonia water mixture. The rate of heat transfer increases for higher values of entry temperature and aqua-ammonia concentration mixture. It is observed that, for an inlet temperature of 80°C for ammonia mixture, the heat load required varies from 870 to 1000 W, as concentration of the mixture increases. However, for the same concentration range with an inlet temperature of 90°C, heat load required is only 700–760 W.

The influence of glycol water mixture flow rate on outlet temperatures of both the fluids, and the heat transfer rates are shown in Fig. 7(c). Mass flow rate of glycol water mixture, at the inlet, has been varied from 80 to 220 LPH. The flow rate of the thermic fluid does not have much effect on the outlet temperature of the ammonia water mixture, and the heat transfer rate. However, as the flow rate of glycol water mixture increases, so does the outlet temperature of the thermic fluid, which then stabilises for higher flow rates. From Fig. 8(d), we observe that the rate of heat transfer remains almost a constant as the flow rate of the hot fluid increases. However, as concentration of ammonia water mixture increases, the heat load required also becomes significantly higher. For 30% ammonia solution, the heat load required is 780 W, whereas, for 50% ammonia solution the heat load increases to 1000 W.

4. Conclusions

Experiments were carried out on a horizontal falling film vapour generator used in a VAR system. A thermodynamic simulation model is developed by using mass and energy balance equations and heat transfer correlations, the developed model is validated with experimental observations. The results obtained from the model are compared with experimental observations, the deviation is in agreeable limits. Thus, it can be said that MATLAB is a useful tool for predicting the outlet conditions in a falling film vapour generator using aqua-ammonia as the working fluid. Using this concept, MATLAB has been used to determine the hot fluid (glycol water mixture) outlet temperature, and the cold fluid (ammonia water mixture), by varying key operating parameters of inlet temperature, mass flow rate of the fluid and its concentration. It is observed that, the results obtained are in correlation with the concepts of heat transfer. Heat load required for the effective operation of the generator, decreases as the aqua-ammonia mixture temperature increases at inlet. This is because, the temperature difference becomes lesser for higher temperatures of the cold fluid. Range of values for the heat load required, decreases with an increase of thermic fluid entry temperature. This is because the hot fluid temperature will be greater than or equal to the cold fluid inlet temperature at that point, for effective operation.

- Heat transfer rates will be higher for 50% ammonia mixture at 80 °C.
- A maximum of 9.8% deviation is observed between experimental and analytical observations for high temperatures.
- A maximum heat transfer rate of 1000 W/m^2 is observed for aqua-ammonia for thermic fluid inlet temperature of 80°C with ammonia concentration of 0.6 by volume.

Further it is observed that the glycol water mixture flow rate increases the outlet temperature of the thermic fluid, which then stabilises for higher flow rates.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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