JORNADAS ACADÉMICAS 2019
cimav CONACYT
25 ANIVERSARIO

Vapor generation of Acetone for an ORC inside a partially filled solar evacuated tube absorber

Kajewole Emmanuel Dami, Ricardo Beltrán-Chacón
Centro de Investigación en Materiales Avanzados, S.C., CIMAV, Miguel de Cervantes 120, Complejo 7 Industrial Chihuahua, Chih. C.P. 31136, México

ABSTRACT

This paper proposes direct steam generation by solar radiation falling on an evacuated tube. Partially filled mass flow of acetone is controlled in a solar evacuated tube collector (ETC) of an Organic Rankine Cycle (ORC), with the purpose of ensuring the generation of vapor at all times irrespective of the irradiance from the sun during the day and night. A system of single pipe in which the subcooled undergoes heating and evaporation process is analyzed controlled by the variable flow. Mathematical equations are derived based on energy and mass balances for system components. A Scilab code is built to simulate the flow of acetone inside the absorber tube and determine properties of acetone along the pipe. Empirical correlations and mathematical models of mass flow, for single and two-phase flow, and heat transfer are used in the simulation. Simulation are run from a subcooled temperature of 60 °C to a saturation temperature of 120 °C, vapor qualities from 1 - 99 percent and solar radiation from 600 - 1000 W/m². Two-phase flow observations showed that the simulation data covered only the fully stratified regimes. The Kattan-Thome-Favrat flow boiling model is used to obtain the two-phase local heat transfer coefficients along the tube. The flow boiling model is also successfully compared to the experimental result of ammonia obtained by Zürcher, O., *et al* [1].

INTRODUCTION

In the presence of the growing global demand for energy, renewable energy provides the most promising solutions. Amongst all other renewable energy resources, solar energy is the most plentiful and permanent till date. The ORC is understood as the most realized one among several proposed Technologies for generating electricity via the utilization of low-grade heat sources. Therefore, it is capable of enhancing energy utilization and reducing greenhouse gas emissions [2].

Direct steam generation (DSG) parabolic trough collector (PTC) solar thermal power plants can work in three different basic operating modes, namely: once-through, recirculation and injection modes although they have drawbacks like complexity and high operating costs [3].

The proposed system uses a variable flow pump to control and vary the mass flow of the fluid depending on the irradiance from the sun which ensures vapor generation in the solar collector, ensuring a constant vapor pressure and temperature at the collector outlet in a partially filled pipe.

Acetone was selected as the most suitable fluid to operate in the cycle. The inlet temperature and pressure are 60 °C and 115 kPa and at the outlet is 120 °C and 604 kPa respectively.

DESCRIPTION AND MODEL OF THE SYSTEM

Subcooled acetone enters the absorber tube and its temperature increases along the length of the absorber tube. When the temperature of the acetone equals to the saturation temperature, nucleate boiling begins. More heat from the sun increases the quality, *x* in the evacuated tube as shown in Figure 1. As acetone flows downstream, dry out occurs. At this point, the heat transfer coefficient decreases because the decrease of thermal conductivity of acetone vapor. The thermodynamic properties of acetone are calculated and evaluated based on Coolprop [4]. Table 1 represents the specifications of the evacuated tube used in this study.

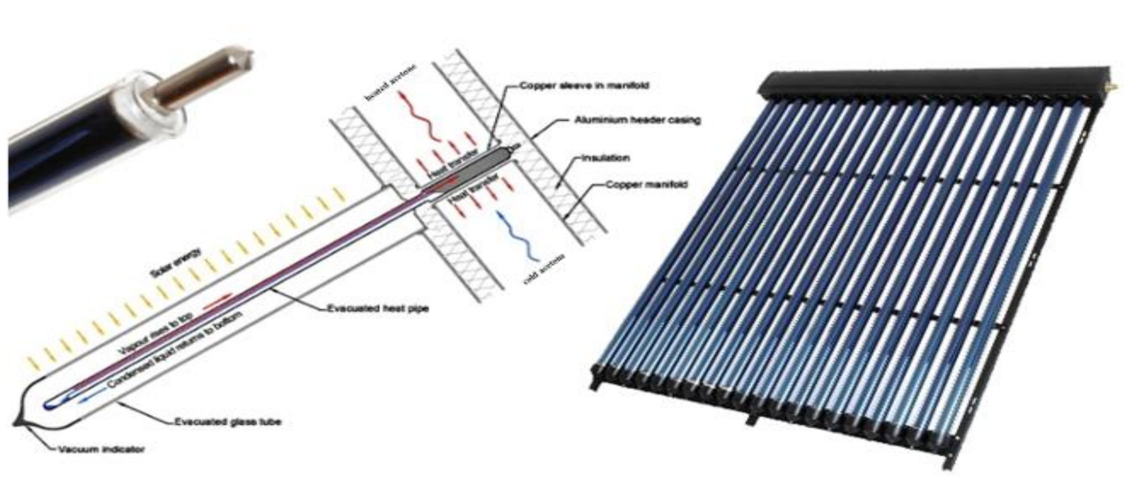

Figure 1: Evacuated tube collector

Table 1. Absorber tube specifications

Absorber tube length	2.196 m
Absorber tube inner diameter	0.020 m
The transmittance factor of tube	0.92
The absorber of the tube	0.93

The absorber tube is divided into n segments and at any irradiance, *I* from the sun, the rate of heat transfer on the fluid in the solar collector is given as:

$$Q = I(\tau \propto) \times A_f \qquad 1$$

where A_f is the area of acetone at the nth segment. The mass flow is then obtained from the energy balance by specifying the required temperatures and latent heat of vaporization of the outlet temperature from the formula below:

$$Q = \left(m \times C_p(T_2 - T_1)\right) + \left(m \times h_{fg}\right) \qquad 2$$

where *Cp* is the average specific heat of the inlet and outlet temperature, T_1 and T_2 are the inlet and outlet temperature and h_{fg} is the latent heat of vaporization of acetone. This ensures that for any irradiance, *I*, there will be a unique mass flow rate, *m* which will ensure the production of vapor at the outlet of the collector.

As the first step in the heat transfer model of Kattan–Thome–Favrat [5], flow regime transition curves G_{strat}, G_{wavy}, G_{mist} and x_{IA} are calculated as presented in Kattan *et al* [6]. After determination of the flow pattern map, the actual local flow regime is determined for the specified combination of quality, *x* and mass flow. Our study shows that the flow regime in the evacuated tube is *Gstrat* which means it is the fully stratified flow.

NUMERICAL VALIDATION

The validation of the result is obtained from the comparison of the experimental and numerical heat transfer coefficient of ammonia [4] at a mass velocity of 20 kg/s with a heat flux of 5.22 kW/m² as shown in figure 2. The model gave an error of -22 %. This signifies that the model is conservative and the control can be worked upon.

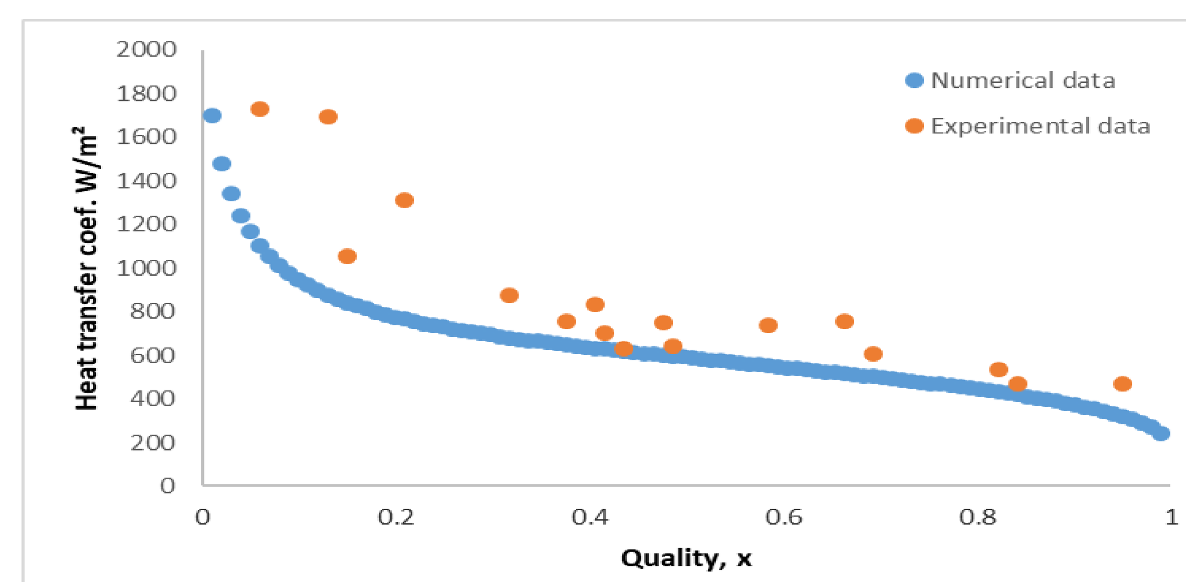

Figure 2: Experimental and Numerical heat transfer of ammonia using Kattan–Thome–Favrat model

RESULTS AND DISCUSSION

Simulation code is developed to obtain the mass flow of acetone as a control to ensure the generation of vapor irrespective of the irradiance from the sun. The mass flow of acetone at a simulated irradiance of 600, 800 and 1000 W/m² are 0.097 g/s, 0.129 g/s and 0.16 g/s respectively. The inlet and outlet temperature are 60 °C and 120 °C. The flow boiling heat transfer coefficient at these mass flow calculated above is obtained from the Kattan-Thome-Favrat model which is shown in figure 3.

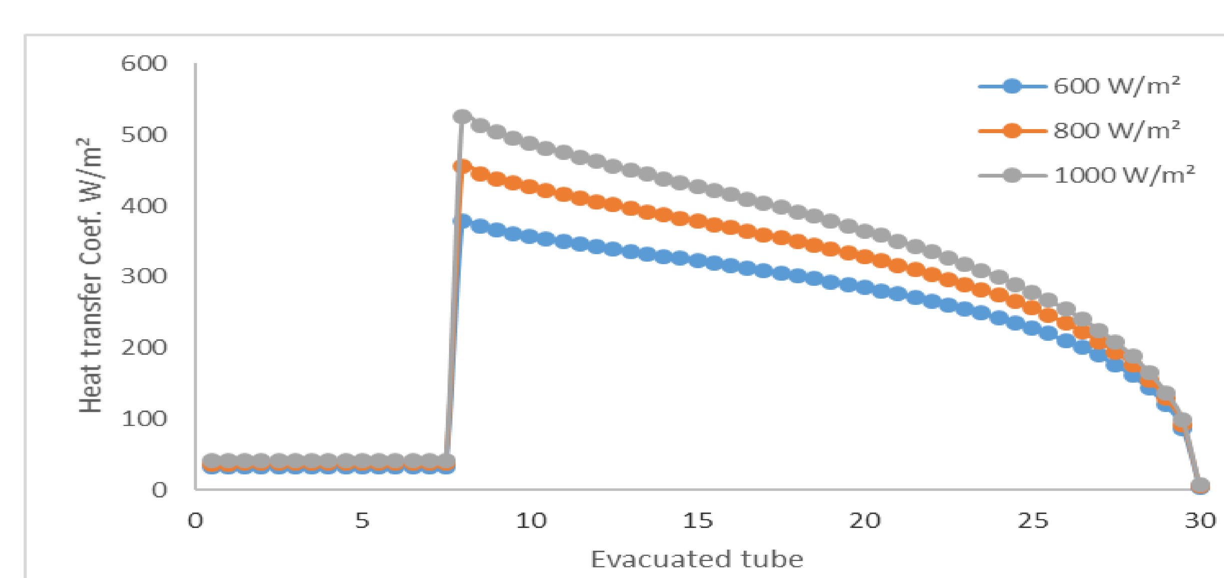

Figure 2: Simulation of the Kattan-Thome-Favrat model for acetone showing the heat transfer coefficient

CONCLUSIONS

The direct steam generated by solar radiation falling on an evacuated tube is analyzed. Two phase flow resulted from evaporation process is considered. The Scilab program shows that there is always a unique mass flow for every irradiance of the sun in a partially filled evacuated tube to ensure the generation of vapor at the end of the tube. Lastly, the heat transfer coefficient of acetone in two phase is obtained using the model of Kattan–Thome–Favrat.

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