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Implementation of Adaptive Observer and Mathematical Model Validation of the Evaporator of an Absorption Heat Transformer

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Abstract: This article presents the implementation of an adaptive observer to validate a falling film evaporator mathematical model. The evaporator consists of four coils, and each coil has four tubes. The heating flow in the first and third coils flows from bottom to top. Meanwhile, the heating flow in the second and fourth coils flows from top to bottom. The mathematical model of the evaporator is parameterized with the geometry data of the experimental device. Since the mathematical model depends on the film breakdown onset Reynolds number (Re_{Onset}) to estimate the evaporator temperatures, an adaptive observer is applied to estimate this unknown parameter (Re_{Onset}). The observer design is developed through the evaporator mathematical model. The research aims to estimate the Re_{Onset} at different operating conditions to accurately estimate the evaporator temperatures since there is no general correlation for estimating it or a sensor to measure this parameter. Once the Re_{Onset} is estimated at different operating conditions, the Re_{Onset} results are injected into the model for validation. The results of implementing the observer showed that the temperature estimation errors are between 0.00003% and 0.02815%. Moreover, the temperatures simulated with the model using the Re_{Onset} estimated with the observers had errors between 0.04012% and 0.14160%.

Keywords: adaptive observer; heat transfer; absorption heat transformer; evaporation process; nested helical heat exchanger

MSC: 80A99; 93A99



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1. Introduction

Falling film evaporation systems are widely studied and used in various industrial processes [1]. Their energy performance largely depends on the film flow, fluid properties, and heat transfer area [2]. The most-studied falling film evaporators are horizontal tube evaporators; their compact construction provides high heat transfer coefficients [3]. However, in the last decade, studies have been conducted on different geometries and surfaces, including helical, rotating, and elliptical tubes [4,5]. Moreover, several studies have been conducted on the different types of falling film flow, for example, droplet, droplet-jet, jet, jet-sheet, and sheet modes [6]. However, in experimental works, these types of studies are limited in providing a comprehensive description of the heat and mass transfer behavior [7], and it is difficult or impossible to monitor the phenomena occurring on the liquid film and the tube wall interface, as well as the heat transfer from the inside of the tube to the fluid [8]. The main limitation is the monitoring of vapor pressure and phase change temperature. Thus, theoretical and experimental studies have been conducted to develop mathematical

models to understand the phenomenology during the evaporation process [9]. Given the aforementioned limitations, models, correlations, mathematical formulations, and various computational tools have been developed to understand the evaporation phenomenon [10]. Some works on modeling falling film evaporators focus on analyzing heat transfer, as well as the effect of the falling film on tubes, such as the study carried out by Tahir et al. [11], who developed a 2D CFD model to study the impact of surface tension and viscosity on the thickness of the falling film in a horizontal tube evaporator for multi-effect desalination (MED). They implemented a multiphase volume of fluid (VOF) model to distinguish between liquid and gas phases and concluded that the evaporator performs better at temperatures close to 358.15 K [11]. On the other hand, the study conducted by Bustamante et al. [12] developed three models to predict the flow regime, the wetted area of the tube, and the heat transfer coefficients for falling film evaporation on horizontal rectangular tubes. They observed that the heat transfer coefficient increases with the mass flow rate or the spacing of the test section. Furthermore, with increasing temperature, the heat transfer coefficient initially rises but decreases after reaching the transition point. These models accurately approximated the experimental data, correctly predicting 82% of the flow regimes [12]. On the other hand, Canela-Sánchez et al. [13] developed a computational model of a helical falling film evaporator with 13 tubes to understand the process behavior and improve performance through energy transfer and system pressure. They observed that the first tube generated the highest heat transfer rate because the temperature difference was the highest due to the inlet saturation condition. They also reported that the heat transfer rate improves at flows around 0.00264 kg/s-m when all the tubes are wetted. Additionally, they developed an alternative evaporator design to increase process performance. They proposed two evaporators with five tubes each instead of a single evaporator with 13 tubes, which increased the heat transfer rate by 21.16% and 18.69% at a mass flow rate per unit length of the tube of 0.00529 and 0.00793 kg/s-m, respectively. Lee et al. [14] studied the heat transfer by evaporation of falling films that descend obliquely over a horizontal elliptical tube. The authors developed a model based on the fluid volume to observe the evaporation effect on the liquid film surface as a flow rate function with temperature. They reported that at low flow rates, the film does not completely cover the tube surface, resulting in the appearance of dry areas and a significant reduction in heat transfer efficiency. However, high flow rates result in a higher heat transfer coefficient, indicating a satisfactory thermal performance, which is similar to previous studies. Furthermore, the authors concluded that adjusting the dispersion angle to 30° can reach an acceptable average heat transfer coefficient. Other investigations have also conducted studies on heat exchanger modeling based on partial differential equations, considering temperature profiles and film mass flow rate to observe the effect of heat and mass transfer [15,16]. Hence, the film mass flow rate is one of the most analyzed parameters through the Reynolds number due to the evaporation phenomenon's complexity when flow falls over the heating tubes and the difficulty of calculating these values [17]. Furthermore, evaporation processes have significant economic and environmental impacts on energy saving, helping to minimize costs and reduce the carbon footprint [18]. On the other hand, the falling film evaporator gives more efficient heat transfer and requires less refrigerant. Hence, it is convenient to use in absorption heat transformers [19]. However, in the study of falling films, various variables in the fluid hydrodynamics directly affect heat and mass transfer, but using theoretical and experimental studies, more accurate models to implement control strategies can be obtained [20]. However, measuring several variables or parameters to describe the phase change phenomenon at the liquid–gas interface during the evaporation process on the tube surface is not an easy task. For solving this problem, adaptive observers can be a possible solution to estimate unknown parameters of the evaporator since observers have been widely used to address parameter estimation in several processes [21–24]. Furthermore, adaptive observers have demonstrated a good performance in estimating different variables or parameters, as shown in [25–27]. Due to their effectiveness, these observers have been applied to design fault diagnosis systems, as shown in [28]. In the literature, different

authors have proposed nonlinear adaptive observer designs considering different classes of systems [29,30]. As mentioned above, the main reason for using these observers is the lack of sensors to measure a specific variable or parameter or the difficulty of installing a sensor inside the devices to obtain measurements. Therefore, this work presents the implementation of an adaptive observer to estimate the Re_{Onset} of a falling film evaporator since this parameter is critical to determining heat transfer accurately. Additionally, the mathematical model of the falling film evaporator is validated using the Re_{Onset} estimated by the observer and the evaporator's experimental temperatures under different operating conditions. This contributes to the experimental falling film evaporators analysis through the accurate parametrization of the mathematical model using an adaptive observer.

2. Materials and Methods

2.1. Absorption Heat Transformer and Experimental Setup

Absorption Heat Transformers (AHTs) are devices capable of recovering heat at an intermediate temperature and raising it to a higher level. These devices consist mainly of four components: a generator (GE), a condenser (CO), an evaporator (EV), and an absorber (AB). These function as heat exchangers with external flows. The configuration of the experimental AHT is shown in Figure 1. The AHT operates with two pressure levels: high pressure in the absorber section (PAB) and low pressure in the generator section (PGE). They also work with three temperature levels: low in the condenser (TCO), medium, as long as the same source feeds both the evaporator and generator (TEV = TGE), and high in the absorber (TAB). The latter is one of the main characteristics of these devices, as it is always higher than that of the other components, as shown in [31]. The AHT includes a measurement instrument system for monitoring variables and controlling the process. Table 1 shows the used measurement instruments in the experimental evaporator.



Figure 1. Experimental absorption heat transformer.

Table 1. Measurement instruments in the evaporator.

Measurable Variable	Measurement Instrument
Pressure	Cole-Parmer model 6807302 differential pressure transducer (Cole-Parmer, Chicago, IL, USA).
Temperature	Dominion Industrial TP100 type thermocouples and aluminum type T thermocouples (Diemech Turbine Solutions, Deland, FL, USA).
Mass flow rate	Cole-Parmer model 3229-25 flowmeters (Cole-Parmer, Chicago, IL, USA).

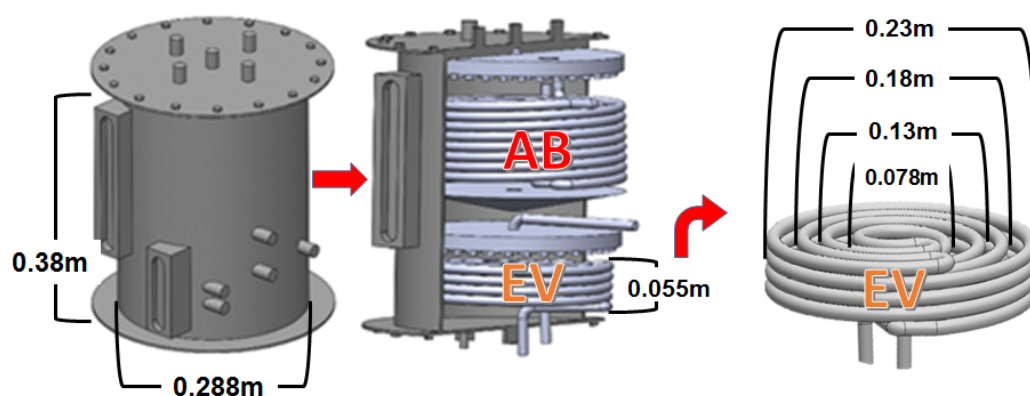
Evaporation Process

Figure 2 shows the geometry and arrangement of the evaporator and absorber inside the shell. Note that the evaporator and absorber are in the same shell to reduce heat and pressure losses. Figure 2, on the left side, shows the evaporator shell geometry, which is 0.38 m long and 0.288 m in diameter. Furthermore, the absorber is above the evaporator, as shown in the middle of the figure. Additionally, Figure 2, on the right side, shows the evaporator geometry, which consists of four nested helical coils made of stainless steel. The dimensions of the evaporator are shown in Table 2.

The evaporation process starts when the refrigerant (water) enters as saturated liquid into the distributor of the evaporator, which comes from the expansion valve connected to the condenser. Then, the falling film is distributed over the external surface of the tubes, and heating flow is supplied inside the tubes. The heating flow transfers the latent heat to the outer surface of the tubes, provoking a phase change from liquid to vapor, and the steam then rises to the absorber.

Table 2. Dimensions of the evaporator.

Evaporator	Coil 1 [m]	Coil 2 [m]	Coil 3 [m]	Coil 4 [m]
Number of turns	4	4	4	4
Length per tube [m]	0.2051	0.3685	0.5256	0.6827
Total Length [m]	0.8206	1.4740	2.1024	2.7307
External coil diameter [m]	0.078	0.13	0.18	0.23
Internal tube diameter [m]	0.00940	0.00940	0.00940	0.00940
External tube diameter [m]	0.0127	0.0127	0.0127	0.0127
Wall thickness [m]	0.00165	0.00165	0.00165	0.00165

**Figure 2.** Geometry and arrangement of the evaporator and absorber at the shell.

2.2. Evaporator Modeling

The evaporator shown in Figure 3 consists of four nested coils, with each coil of four tubes. As shown in the figure, the heating flow in the first and third coils flows from the bottom to the top of the evaporator, and in the second and fourth coils, the heating flow flows from the top to the bottom of the evaporator. According to the figure, the heating flow flows as follows: the heating flow enters the evaporator through coil 1 through tube 4, continuing up the coil through tube 1. Then, the heating flow passes to coil 2 through

tube 5, changing the flow direction at each coil change, and the fluid comes out in tube 8. Then, the heating flow enters coil 3 in tube 12, comes out through tube 9, and passes to coil 4 through tube 13. Finally, the heating flow comes out of the system through tube 16. Each evaporator coil was modeled as a subsystem of four pairs differential equations, as shown in Equations (1)–(4); the model programming was carried out in the MATLAB® software version R2013a. The evaporator geometry and flow directions are considered in the volume and heat transfer area equations and through the arrangement of the differential equations shown in Equations (1)–(4), respectively. For instance, the heating flow inlet is in tube 4 of coil 1, and its outlet is in tube 16 of coil 4. Whilst, the inlet of the falling film is spread in tubes 1, 5, 9, and 13 of the four coils, and the outlet falling film temperature is in tubes 4, 8, 12, and 16 of coils 1, 2, 3, and 4, respectively.

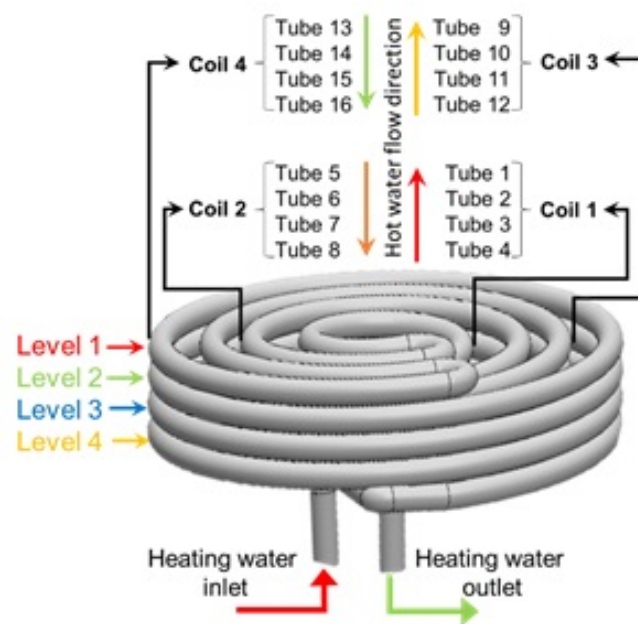


Figure 3. Schematic of the geometric configuration of the evaporator model.

Model assumptions

The following are the assumptions used in this model:

- The evaporator efficiency is 70% [31] due to the heat losses to the environment and some uncertainty of the measurements.
- The pressure of the system is constant.
- The heat transfer coefficients are calculated according to Nusselt's theory [13].

The energy balance of the evaporator for the film side at the subcooling condition and the energy balance for the heating fluid can be represented by the differential equations system [32,33] given in Equations (1)–(4). Each set of equations corresponds to the specific evaporator coil shown in Figure 3, and the arrow direction corresponds to the flow direction of the heating flow.

$$\text{coil}_1 \uparrow \left\{ \begin{array}{l} \frac{d(M_{Flm}^1 H_{Flm}^1)}{dt} = \dot{m}_{Flm}^{i1} H_{Flm}^{i1} - \dot{m}_{Flm}^{o1} H_{Flm}^{o1} - \dot{m}_{Vap}^{o1} H_{Vap}^{o1} + \dot{Q}_{Trn}^1, \\ M_{Tub}^1 C_{pTub}^1 \frac{d\hat{T}_{Tub}^1}{dt} = \dot{m}_{Tub}^1 C_{pTub}^1 (T_{Tub}^{o2} - T_{Tub}^{o1}) - \dot{Q}_{Trn}^1, \\ \frac{d(M_{Flm}^2 H_{Flm}^2)}{dt} = \dot{m}_{Flm}^{o1} H_{Flm}^{o1} - \dot{m}_{Flm}^{o2} H_{Flm}^{o2} - \dot{m}_{Vap}^{o2} H_{Vap}^{o2} + \dot{Q}_{Trn}^2, \\ M_{Tub}^2 C_{pTub}^2 \frac{d\hat{T}_{Tub}^2}{dt} = \dot{m}_{Tub}^2 C_{pTub}^2 (T_{Tub}^{o3} - T_{Tub}^{o2}) - \dot{Q}_{Trn}^2, \\ \frac{d(M_{Flm}^3 H_{Flm}^3)}{dt} = \dot{m}_{Flm}^{o2} H_{Flm}^{o2} - \dot{m}_{Flm}^{o3} H_{Flm}^{o3} - \dot{m}_{Vap}^{o3} H_{Vap}^{o3} + \dot{Q}_{Trn}^3, \\ M_{Tub}^3 C_{pTub}^3 \frac{d\hat{T}_{Tub}^3}{dt} = \dot{m}_{Tub}^3 C_{pTub}^3 (T_{Tub}^{o4} - T_{Tub}^{o3}) - \dot{Q}_{Trn}^3, \\ \frac{d(M_{Flm}^4 H_{Flm}^4)}{dt} = \dot{m}_{Flm}^{o3} H_{Flm}^{o3} - \dot{m}_{Flm}^{o4} H_{Flm}^{o4} - \dot{m}_{Vap}^{o4} H_{Vap}^{o4} + \dot{Q}_{Trn}^4, \\ M_{Tub}^4 C_{pTub}^4 \frac{d\hat{T}_{Tub}^4}{dt} = \dot{m}_{Tub}^4 C_{pTub}^4 (T_{Tub}^i - T_{Tub}^{o4}) - \dot{Q}_{Trn}^4. \end{array} \right. \quad (1)$$

$$\text{coil}_2 \downarrow \left\{ \begin{array}{l} \frac{d(M_{Flm}^5 H_{Flm}^5)}{dt} = \dot{m}_{Flm}^{i5} H_{Flm}^{i5} - \dot{m}_{Flm}^{o5} H_{Flm}^{o5} - \dot{m}_{Vap}^{o5} H_{Vap}^{o5} + \dot{Q}_{Trn}^5, \\ M_{Tub}^5 C_{pTub}^5 \frac{d\hat{T}_{Tub}^5}{dt} = \dot{m}_{Tub}^5 C_{pTub}^5 (T_{Tub}^{o1} - T_{Tub}^{o5}) - \dot{Q}_{Trn}^5, \\ \frac{d(M_{Flm}^6 H_{Flm}^6)}{dt} = \dot{m}_{Flm}^{o5} H_{Flm}^{o5} - \dot{m}_{Flm}^{o6} H_{Flm}^{o6} - \dot{m}_{Vap}^{o6} H_{Vap}^{o6} + \dot{Q}_{Trn}^6, \\ M_{Tub}^6 C_{pTub}^6 \frac{d\hat{T}_{Tub}^6}{dt} = \dot{m}_{Tub}^6 C_{pTub}^6 (T_{Tub}^{o5} - T_{Tub}^{o6}) - \dot{Q}_{Trn}^6, \\ \frac{d(M_{Flm}^7 H_{Flm}^7)}{dt} = \dot{m}_{Flm}^{o6} H_{Flm}^{o6} - \dot{m}_{Flm}^{o7} H_{Flm}^{o7} - \dot{m}_{Vap}^{o7} H_{Vap}^{o7} + \dot{Q}_{Trn}^7, \\ M_{Tub}^7 C_{pTub}^7 \frac{d\hat{T}_{Tub}^7}{dt} = \dot{m}_{Tub}^7 C_{pTub}^7 (T_{Tub}^{o6} - T_{Tub}^{o7}) - \dot{Q}_{Trn}^7, \\ \frac{d(M_{Flm}^8 H_{Flm}^8)}{dt} = \dot{m}_{Flm}^{o7} H_{Flm}^{o7} - \dot{m}_{Flm}^{o8} H_{Flm}^{o8} - \dot{m}_{Vap}^{o8} H_{Vap}^{o8} + \dot{Q}_{Trn}^8, \\ M_{Tub}^8 C_{pTub}^8 \frac{d\hat{T}_{Tub}^8}{dt} = \dot{m}_{Tub}^8 C_{pTub}^8 (T_{Tub}^{o7} - T_{Tub}^{o8}) - \dot{Q}_{Trn}^8. \end{array} \right. \quad (2)$$

$$\text{coil}_3 \uparrow \left\{ \begin{array}{l} \frac{d(M_{Flm}^9 H_{Flm}^9)}{dt} = \dot{m}_{Flm}^{i9} H_{Flm}^{i9} - \dot{m}_{Flm}^{o9} H_{Flm}^{o9} - \dot{m}_{Vap}^{o9} H_{Vap}^{o9} + \dot{Q}_{Trn}^9, \\ M_{Tub}^9 C_{pTub}^9 \frac{d\hat{T}_{Tub}^9}{dt} = \dot{m}_{Tub}^9 C_{pTub}^9 (T_{Tub}^{o10} - T_{Tub}^{o9}) - \dot{Q}_{Trn}^9, \\ \frac{d(M_{Flm}^{10} H_{Flm}^{10})}{dt} = \dot{m}_{Flm}^{o9} H_{Flm}^{o9} - \dot{m}_{Flm}^{o10} H_{Flm}^{o10} - \dot{m}_{Vap}^{o10} H_{Vap}^{o10} + \dot{Q}_{Trn}^{10}, \\ M_{Tub}^{10} C_{pTub}^{10} \frac{d\hat{T}_{Tub}^{10}}{dt} = \dot{m}_{Tub}^{10} C_{pTub}^{10} (T_{Tub}^{o11} - T_{Tub}^{o10}) - \dot{Q}_{Trn}^{10}, \\ \frac{d(M_{Flm}^{11} H_{Flm}^{11})}{dt} = \dot{m}_{Flm}^{o10} H_{Flm}^{o10} - \dot{m}_{Flm}^{o11} H_{Flm}^{o11} - \dot{m}_{Vap}^{o11} H_{Vap}^{o11} + \dot{Q}_{Trn}^{11}, \\ M_{Tub}^{11} C_{pTub}^{11} \frac{d\hat{T}_{Tub}^{11}}{dt} = \dot{m}_{Tub}^{11} C_{pTub}^{11} (T_{Tub}^{o12} - T_{Tub}^{o11}) - \dot{Q}_{Trn}^{11}, \\ \frac{d(M_{Flm}^{12} H_{Flm}^{12})}{dt} = \dot{m}_{Flm}^{o11} H_{Flm}^{o11} - \dot{m}_{Flm}^{o12} H_{Flm}^{o12} - \dot{m}_{Vap}^{o12} H_{Vap}^{o12} + \dot{Q}_{Trn}^{12}, \\ M_{Tub}^{12} C_{pTub}^{12} \frac{d\hat{T}_{Tub}^{12}}{dt} = \dot{m}_{Tub}^{12} C_{pTub}^{12} (T_{Tub}^{o8} - T_{Tub}^{o12}) - \dot{Q}_{Trn}^{12}. \end{array} \right. \quad (3)$$

$$\text{coil}_4 \downarrow \left\{ \begin{array}{l} \frac{d(M_{Flm}^{13} H_{Flm}^{13})}{dt} = \dot{m}_{Flm}^{i13} H_{Flm}^{i13} - \dot{m}_{Flm}^{o13} H_{Flm}^{o13} - \dot{m}_{Vap}^{o13} H_{Vap}^{o13} + \dot{Q}_{Trn}^{13}, \\ M_{Tub}^{13} C_{pTub}^{13} \frac{d\hat{T}_{Tub}^{13}}{dt} = \dot{m}_{Tub}^{13} C_{pTub}^{13} (T_{Tub}^{o9} - T_{Tub}^{o13}) - \dot{Q}_{Trn}^{13}, \\ \frac{d(M_{Flm}^{14} H_{Flm}^{14})}{dt} = \dot{m}_{Flm}^{o13} H_{Flm}^{o13} - \dot{m}_{Flm}^{o14} H_{Flm}^{o14} - \dot{m}_{Vap}^{o14} H_{Vap}^{o14} + \dot{Q}_{Trn}^{14}, \\ M_{Tub}^{14} C_{pTub}^{14} \frac{d\hat{T}_{Tub}^{14}}{dt} = \dot{m}_{Tub}^{14} C_{pTub}^{14} (T_{Tub}^{o13} - T_{Tub}^{o14}) - \dot{Q}_{Trn}^{14}, \\ \frac{d(M_{Flm}^{15} H_{Flm}^{15})}{dt} = \dot{m}_{Flm}^{o14} H_{Flm}^{o14} - \dot{m}_{Flm}^{o15} H_{Flm}^{o15} - \dot{m}_{Vap}^{o15} H_{Vap}^{o15} + \dot{Q}_{Trn}^{15}, \\ M_{Tub}^{15} C_{pTub}^{15} \frac{d\hat{T}_{Tub}^{15}}{dt} = \dot{m}_{Tub}^{15} C_{pTub}^{15} (T_{Tub}^{o14} - T_{Tub}^{o15}) - \dot{Q}_{Trn}^{15}, \\ \frac{d(M_{Flm}^{16} H_{Flm}^{16})}{dt} = \dot{m}_{Flm}^{o15} H_{Flm}^{o15} - \dot{m}_{Flm}^{o16} H_{Flm}^{o16} - \dot{m}_{Vap}^{o16} H_{Vap}^{o16} + \dot{Q}_{Trn}^{16}, \\ M_{Tub}^{16} C_{pTub}^{16} \frac{d\hat{T}_{Tub}^{16}}{dt} = \dot{m}_{Tub}^{16} C_{pTub}^{16} (T_{Tub}^{o15} - T_{Tub}^{o16}) - \dot{Q}_{Trn}^{16}. \end{array} \right. \quad (4)$$

Equation (5) represents the heat transfer rate ($\dot{Q}_{Trn}$), $n = 1, 2, \dots, 16$.

$$\dot{Q}_{Trn}^n = \eta_{Wet} U A_{Trn} \Delta T, \quad (5)$$

where U represents the overall heat transfer coefficient. U depends on the convective coefficients of the falling film side and the heating fluid [13]. A_{Trn} represents the heat transfer area. ΔT is the temperature difference, which is an approximation of a logarithmic mean temperature difference and it is calculated by Equation (6) [13]. In Equation (6), $\Delta T_1 = T_{Tub}^o - T_{Flm}^o$ and $\Delta T_2 = T_{Tub}^i - T_{Flm}^i$. Finally, η_{Wet} represents the wetting efficiency. This parameter is the fraction of the tube humidified by the falling film calculated by Equation (7) [34].

$$\Delta T = (\Delta T_1 \Delta T_2)^{\frac{(\Delta T_1 + \Delta T_2)}{2}} \quad (6)$$

$$\eta_{Wet} = \begin{cases} 1 & \text{if } Re_{Flm} \geq Re_{Onset} \\ Re_{Flm} / Re_{Onset} & \text{if } Re_{Flm} < Re_{Onset}, \end{cases} \quad (7)$$

where Re_{Onset} is the film breakdown onset Reynolds number and is the parameter to estimate in this work. Re_{Onset} determines the onset of the dryout on the tubes due to the breaking of the falling film [34,35]. From the Re_{Onset} , the wetting efficiency begins to decrease proportionally when the Re decreases, as shown in Equation (7). In this work, the Re_{Onset} value is unknown because it is difficult to measure experimentally, and there is no correlation to calculate it accurately. Hence, this is the parameter to estimate in this work. Note that Re_{Onset} can be estimated only in the operation condition of partial wetting because, in full wetting conditions, different values of Re_{Onset} can be calculated since Re_{Flm} is higher than Re_{Onset} , as shown in Equation (7).

2.3. Nonlinear Adaptive Observer

This section presents the nonlinear adaptive observer designs applied to the evaporator. The observer was mathematically developed by Besancon [29]. According to the author, a nonlinear system of the form given in Equation (8) can be represented in the nonlinear adaptive observer form shown in (9) if the nonlinear system satisfies the criteria for the nonlinear adaptive observer given in [29].

$$\begin{aligned} \dot{\kappa}_1 &= \alpha(\kappa_1, \kappa_2, u, t) + \beta(\kappa_1, \kappa_2, u, t)\Theta, \\ \dot{\kappa}_2 &= Z(\kappa_1, \kappa_2, u, t), \end{aligned} \quad (8)$$

where $\kappa_1 \in \mathbb{R}^p$ and $\kappa_2 \in \mathbb{R}^r$ are the measurable output and non-measurable states vectors, respectively, $u \in \mathbb{R}^m$ denotes the input vector, and $\Theta \in \mathbb{R}^q$ represents the unknown parameters vector. $\alpha(\kappa_1, \kappa_2, u, t)$ and $\beta(\kappa_1, \kappa_2, u, t)$ are two globally Lipschitz functions with respect to κ_2 .

$$\begin{aligned} \dot{\hat{\kappa}}_1 &= \alpha(\kappa_1, \hat{\kappa}_2, u, t) + \beta(\kappa_1, \hat{\kappa}_2, u, t)\hat{\Theta} - K_y(\hat{\kappa}_1 - \kappa_1); \quad K_y > 0, \\ \dot{\hat{\kappa}}_2 &= Z(\kappa_1, \hat{\kappa}_2, u, t), \\ \dot{\hat{\Theta}} &= -K_\Theta \beta^T(\kappa_1, \hat{\kappa}_2, u, t)(\hat{\kappa}_1 - \kappa_1)^T; \quad K_\Theta > 0, \end{aligned} \quad (9)$$

where $\|\hat{\kappa}_1(t) - \kappa_1(t)\|$ y $\|\hat{\kappa}_2(t) - \kappa_2(t)\|$ are the estimation errors for the measured and unmeasured states, respectively. $K_y > 0$ and $K_\Theta > 0$ are the observer's gains.

Nonlinear Adaptive Observer Model

This section presents the nonlinear adaptive observer model. The system shown in Equation (10) represents the temperature and parameter (Re_{Onset}) calculated in the tubes of the evaporator where $\Theta = 1/Re_{Onset}$.

$$\begin{aligned}
\frac{d\hat{H}_{Flm}^{16}}{dt} &= \frac{\dot{m}_{Flm}^{o15} H_{Flm}^{o15} - \dot{m}_{Flm}^{o16} H_{Flm}^{o16} - \dot{m}_{Vap}^{o16} H_{Vap}^{o16}}{M_{Flm}^{16}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{16}}{M_{Flm}^{16}} \Theta_{Flm} - K_y (\hat{H}_{Flm}^{o16} - H_{Flm}^{o16}), \\
\frac{d\hat{T}_{Tub}^{16}}{dt} &= \frac{\dot{m}_{Tub}^{16} C_{pTub}^{16} \Delta T_{Tub}}{M_{Tub}^{16} C_{pTub}^{16}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{16}}{M_{Tub}^{16} C_{pTub}^{16}} \Theta_{Tub} - K_y (\hat{T}_{Tub}^{o16} - T_{Tub}^{o16}), \\
\frac{d\hat{H}_{Flm}^{15}}{dt} &= \frac{\dot{m}_{Flm}^{o14} H_{Flm}^{o14} - \dot{m}_{Flm}^{o15} H_{Flm}^{o15} - \dot{m}_{Vap}^{o15} H_{Vap}^{o15}}{M_{Flm}^{15}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{15}}{M_{Flm}^{15}} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^{15}}{dt} &= \frac{\dot{m}_{Tub}^{15} C_{pTub}^{15} \Delta T_{Tub}}{M_{Tub}^{15} C_{pTub}^{15}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{15}}{M_{Tub}^{15} C_{pTub}^{15}} \Theta_{Tub}, \\
\frac{d\hat{H}_{Flm}^{14}}{dt} &= \frac{\dot{m}_{Flm}^{o13} H_{Flm}^{o13} - \dot{m}_{Flm}^{o14} H_{Flm}^{o14} - \dot{m}_{Vap}^{o14} H_{Vap}^{o14}}{M_{Flm}^{14}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{14}}{M_{Flm}^{14}} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^{14}}{dt} &= \frac{\dot{m}_{Tub}^{14} C_{pTub}^{14} \Delta T_{Tub}}{M_{Tub}^{14} C_{pTub}^{14}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{14}}{M_{Tub}^{14} C_{pTub}^{14}} \Theta_{Tub}, \\
\frac{d\hat{H}_{Flm}^{13}}{dt} &= \frac{\dot{m}_{Flm}^{o12} H_{Flm}^{o12} - \dot{m}_{Flm}^{o13} H_{Flm}^{o13} - \dot{m}_{Vap}^{o13} H_{Vap}^{o13}}{M_{Flm}^{13}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{13}}{M_{Flm}^{13}} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^{13}}{dt} &= \frac{\dot{m}_{Tub}^{13} C_{pTub}^{13} \Delta T_{Tub}}{M_{Tub}^{13} C_{pTub}^{13}} + \frac{Re_{Flm} UA_{Trn} \Delta T^{13}}{M_{Tub}^{13} C_{pTub}^{13}} \Theta_{Tub}, \\
&\vdots \\
\frac{d\hat{H}_{Flm}^4}{dt} &= \frac{\dot{m}_{Flm}^{o3} H_{Flm}^{o3} - \dot{m}_{Flm}^{o4} H_{Flm}^{o4} - \dot{m}_{Vap}^{o4} H_{Vap}^{o4}}{M_{Flm}^4} + \frac{Re_{Flm} UA_{Trn} \Delta T^4}{M_{Flm}^4} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^4}{dt} &= \frac{\dot{m}_{Tub}^4 C_{pTub}^4 \Delta T_{Tub}}{M_{Tub}^4 C_{pTub}^4} + \frac{Re_{Flm} UA_{Trn} \Delta T^4}{M_{Tub}^4 C_{pTub}^4} \Theta_{Tub}, \\
\frac{d\hat{H}_{Flm}^3}{dt} &= \frac{\dot{m}_{Flm}^{o2} H_{Flm}^{o2} - \dot{m}_{Flm}^{o3} H_{Flm}^{o3} - \dot{m}_{Vap}^{o3} H_{Vap}^{o3}}{M_{Flm}^3} + \frac{Re_{Flm} UA_{Trn} \Delta T^3}{M_{Flm}^3} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^3}{dt} &= \frac{\dot{m}_{Tub}^3 C_{pTub}^3 \Delta T_{Tub}}{M_{Tub}^3 C_{pTub}^3} + \frac{Re_{Flm} UA_{Trn} \Delta T^3}{M_{Tub}^3 C_{pTub}^3} \Theta_{Tub}, \\
\frac{d\hat{H}_{Flm}^2}{dt} &= \frac{\dot{m}_{Flm}^{o1} H_{Flm}^{o1} - \dot{m}_{Flm}^{o2} H_{Flm}^{o2} - \dot{m}_{Vap}^{o2} H_{Vap}^{o2}}{M_{Flm}^2} + \frac{Re_{Flm} UA_{Trn} \Delta T^2}{M_{Flm}^2} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^2}{dt} &= \frac{\dot{m}_{Tub}^2 C_{pTub}^2 \Delta T_{Tub}}{M_{Tub}^2 C_{pTub}^2} + \frac{Re_{Flm} UA_{Trn} \Delta T^2}{M_{Tub}^2 C_{pTub}^2} \Theta_{Tub}, \\
\frac{d\hat{H}_{Flm}^1}{dt} &= \frac{\dot{m}_{Flm}^1 H_{Flm}^{o1} - \dot{m}_{Flm}^{o1} H_{Flm}^{o1} - \dot{m}_{Vap}^{o1} H_{Vap}^{o1}}{M_{Flm}^1} + \frac{Re_{Flm} UA_{Trn} \Delta T^1}{M_{Flm}^1} \Theta_{Flm}, \\
\frac{d\hat{T}_{Tub}^1}{dt} &= \frac{\dot{m}_{Tub}^1 C_{pTub}^1 \Delta T_{Tub}}{M_{Tub}^1 C_{pTub}^1} + \frac{Re_{Flm} UA_{Trn} \Delta T^1}{M_{Tub}^1 C_{pTub}^1} \Theta_{Tub}, \\
\frac{d\hat{\Theta}_{Flm}^{16}}{dt} &= -K_{\Theta} \frac{Re_{Flm} UA_{Trn} \Delta T^{16}}{M_{Flm}^{16}} (\hat{H}_{Flm}^{o16} - H_{Flm}^{o16}), \\
\frac{d\hat{\Theta}_{Tub}^{16}}{dt} &= -K_{\Theta} \frac{Re_{Flm} UA_{Trn} \Delta T^{16}}{M_{Tub}^{16} C_{pTub}^{16}} (\hat{T}_{Tub}^{o16} - T_{Tub}^{o16}),
\end{aligned}
\tag{10}$$

3. Results and Discussion

3.1. Parameter Estimation Results

The aim of estimating accurately the Re_{Onset} is to reduce the evaporator modeling uncertainties. Hence, this section presents the implementation of a nonlinear adaptive observer [29] to estimate the Re_{Onset} . The estimation of the Re_{Onset} was carried out using nine experimental tests at steady state divided into three simulations. An evaporator efficiency of 70% is considered in these operating conditions [31]. The first simulation was performed using the operating conditions shown in Table 3.

Table 3. Experimental operating conditions for simulation 1.

Test Number	$\dot{m}_{Tub}^i$ [kg/s]	T_{Tub}^i [°C]	T_{mTub}^o [°C]	$\dot{m}_{Flm}^i$ [kg/s]	T_{mFlm}^i [°C]	$T_{mFlm}^{Sl}(P)$ [°C]	P [kPa]
1	0.1301	78.96	77.28	0.000392	35.50	69.59	30.66
2	0.1299	81.95	80.08	0.000521	37.10	70.21	31.49
3	0.1296	85.14	82.83	0.000661	36.79	70.40	31.75

Figure 4 shows the estimation results of Re_{Onset} . Note that the initial value of Re_{Onset} was set at 17.5. In the figure, it can be observed that Re_{Onset} begins to stabilize approximately

at 25 s. After 27 s, the estimation for the next tests is performed, and the Re_{Onset} value increases abruptly because the operating conditions are changed from one steady state to another. For tests 2 and 3, after approximately 25 s, Re_{Onset} also tends to stabilize. The estimated values of Re_{Onset} for tests 1, 2, and 3, were 16.86, 21.56, and 23.33, respectively.

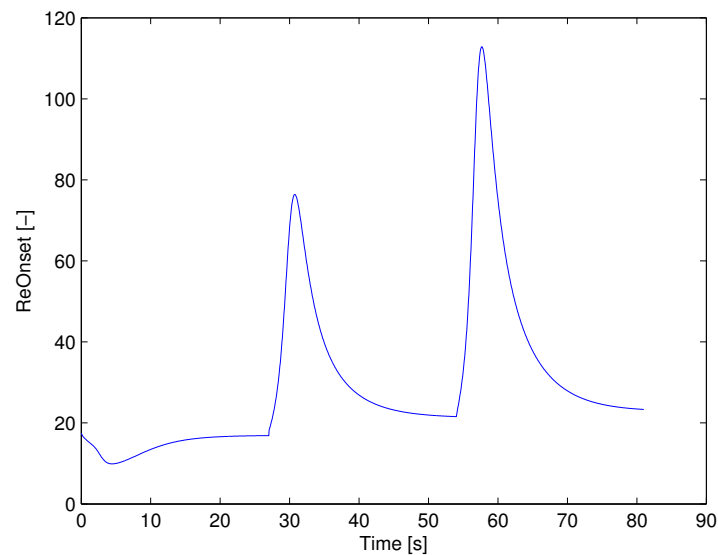


Figure 4. Estimated film breakdown onset Reynolds number of simulation 1.

Figure 5 shows the simulated temperature dynamic. Note that the simulated temperature dynamic exhibits similar behavior to the Re_{Onset} . Moreover, Figure 5 shows that the simulated temperature approaches the experimental temperature (green line) during the simulation, approximately 25 s after the simulation started. Figure 6 shows the estimation errors between the experimental and simulated temperature, which were calculated according to the following equation $error = \left| \frac{T_{Exp} - T_{Tub,1}^0}{T_{Exp}} \right| * 100\%$. The estimation errors were 0.00580%, 0.00796%, and 0.0486%.

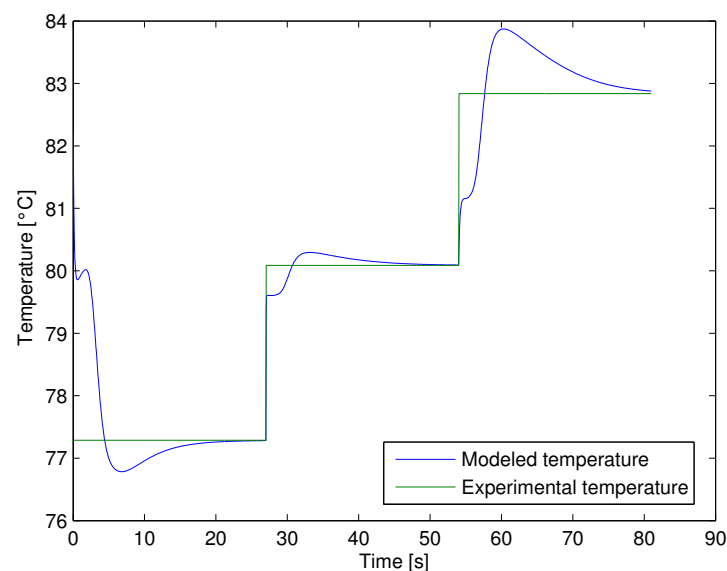


Figure 5. Experimental and modeled temperatures of simulation 1.

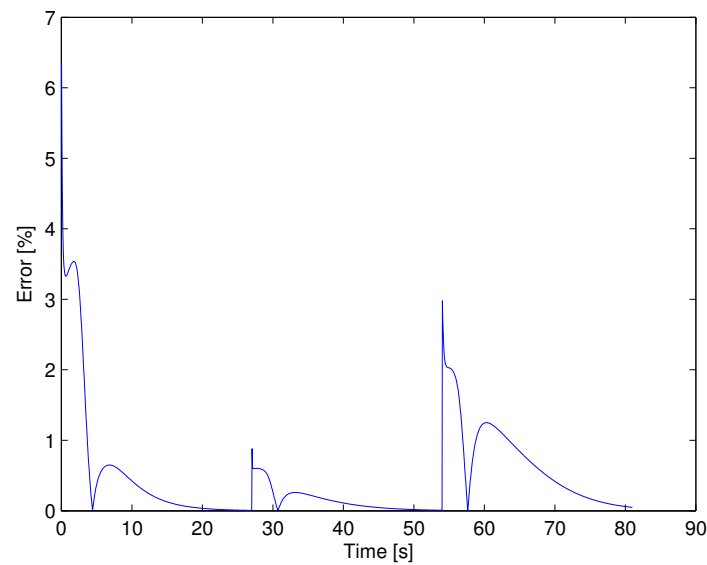


Figure 6. Estimation errors of simulation 1.

The operating conditions to perform the second simulation are shown in Table 4; note that the evaporator temperature varies from 81.90 to 85.00 °C.

Table 4. Experimental operating conditions for simulation 2.

Test Number	$\dot{m}_{Tub}^i$ [kg/s]	Tm_{Tub}^i [°C]	Tm_{Tub}^o [°C]	$\dot{m}_{Flm}^i$ [kg/s]	Tm_{Flm}^i [°C]	$Tm_{Flm}^{Sl}(P)$ [°C]	P [kPa]
1	0.0978	81.90	78.71	0.000591	39.70	71.05	32.7
2	0.0976	85.00	81.12	0.000710	41.20	73.05	35.6

Figure 7 shows the simulated Re_{Onset} dynamic. The estimated values of the Re_{Onset} in tests 1 and 2 were 16.17 and 16.28, respectively. Figure 8 shows that the simulated temperatures (blue line) reached the experimental temperature (green line). Figure 9 shows the estimation errors between the experimental and simulated temperatures, which were calculated according to the following equation: $error = \left| \frac{T_{Exp} - T_{Tub,1}^o}{T_{Exp}} \right| * 100\%$. The estimation errors were 0.00042% and 0.00276%.

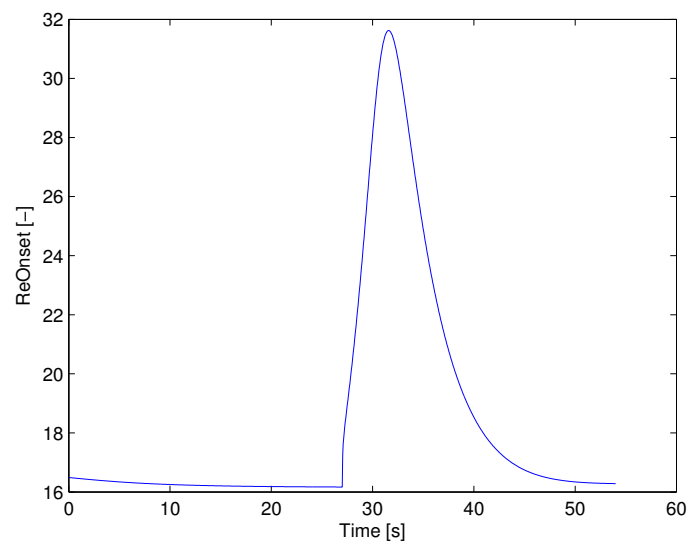


Figure 7. Estimated film breakdown onset Reynolds number of simulation 2.

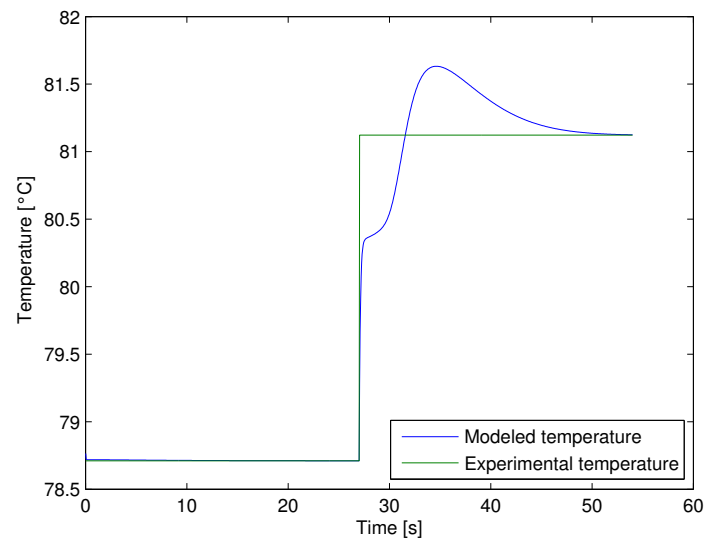


Figure 8. Experimental and modeled temperatures of simulation 2.

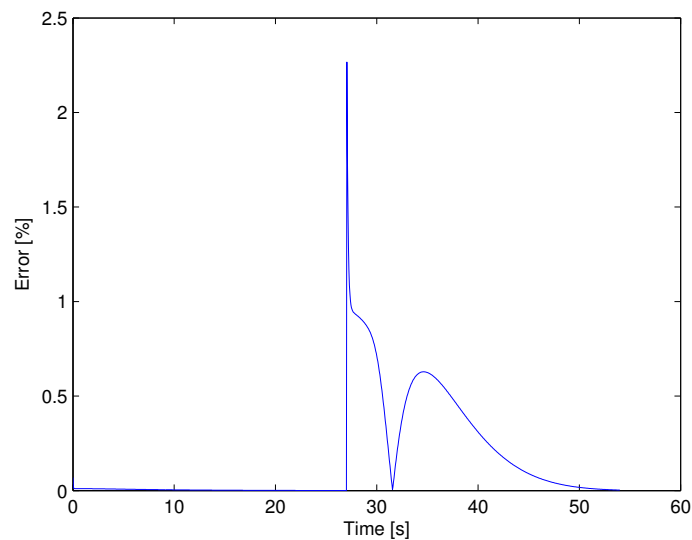


Figure 9. Estimation errors of simulation 2.

The operating conditions to perform the third simulation for estimating the Re_{Onset} are shown in Table 5; note that the evaporator temperature varies from 75.69 to 84.81 °C.

Table 5. Experimental operating conditions for simulation 3.

Test Number	$\dot{m}_{Tub}^i$ [kg/s]	Tm_{Tub}^i [°C]	Tm_{Tub}^o [°C]	$\dot{m}_{Flm}^i$ [kg/s]	Tm_{Flm}^i [°C]	$Tm_{Flm}^{Sl}(P)$ [°C]	P [kPa]
1	0.0980	75.69	73.57	0.00041297	33.01	70.47	31.9
2	0.0979	78.99	76.55	0.00043277	34.06	72.57	34.9
3	0.0977	81.98	79.20	0.00047244	35.49	74.50	37.8
4	0.0975	84.81	81.76	0.00051208	36.73	75.45	39.3

Figure 10 shows the simulated Re_{Onset} dynamic. In the third simulation, the estimated values of the Re_{Onset} from the first, second, third, and fourth tests were 11.19, 11.59, 11.74, and 11.93, respectively. Figure 11 shows that the simulated temperatures (blue line) fit the experimental temperature (green line). On the other hand, Figure 12 shows the estimation errors between the experimental and simulated temperature. The errors from the first, second, third, and fourth tests were 0.00003%, 0.01599%, 0.02224%, and 0.02815%, respectively.

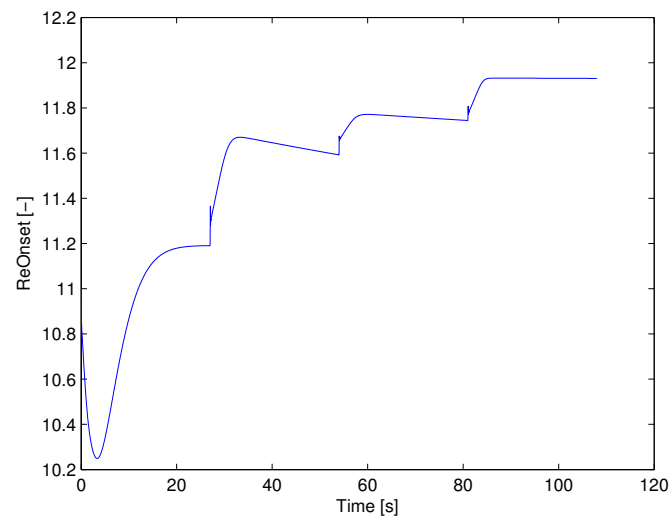


Figure 10. Estimated film breakdown onset Reynolds number of simulation 3.

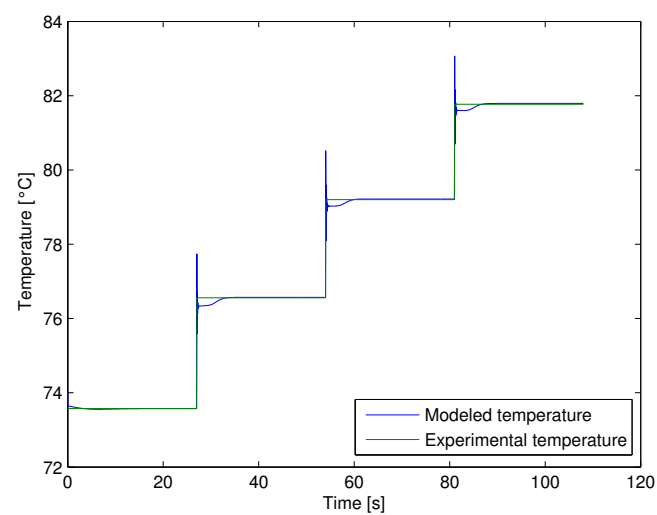


Figure 11. Experimental and modeled temperatures of simulation 3.

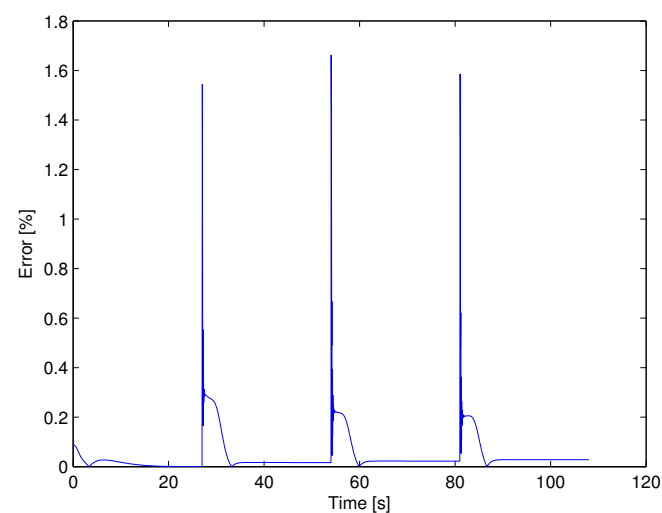


Figure 12. Estimation errors of simulation 3.

Finally, Table 6 shows the values of Re_{Onset} of all tests, which are between 11.19 and 23.33. Moreover, the results show that the estimated temperature with the observer presents

low estimation errors from 0.00003% to 0.02815%. From the results, we can conclude that the Re_{Onset} varies depending on the evaporator operating condition. Regarding the Re_{Onset} estimation, several works have been proposed in the literature. For example, Canela-Sanchez et al. [36] estimated the Re_{Onset} of a falling film evaporator using a Dual Extended Kalman Filter. The results showed Re_{Onset} values between 34.94 and 44.32; these vary according to the evaporator geometry and operating condition. In other works [35,37], the authors calculated Re_{Onset} values around 70 and 185, respectively. However, the geometries of the falling film heat exchangers investigated in [35,37] were not helical, had different tube types, and in [35], absorption is presented. This reaffirms that the Re_{Onset} behavior depends on the geometry, operating conditions, and the physical phenomena of heat exchangers.

Table 6. Parameter estimation results.

Simulation	Test Number	$Re_{Onset,Tub}$	Tm_{Exp} [°C]	Tm_{Obs} [°C]	$Error_{Tub}$ [%]
1	1	16.86	77.2855	77.2810	0.00580
	2	21.56	80.0865	80.0928	0.00796
	3	23.33	82.8375	82.8778	0.04860
2	1	16.16	78.7102	78.7105	0.00042
	2	16.28	81.1223	81.1245	0.00276
3	1	11.19	73.5761	73.5761	0.00003
	2	11.59	76.5684	76.5561	0.01599
	3	11.74	79.2185	79.2009	0.02224
	4	11.93	81.7913	81.7683	0.02815

3.2. Model Validation Results

In this section, the results of the third simulation were validated by performing a simulation using the operation condition of Table 5 and the estimated $Re_{Onset,Tub}$ for each test. The third simulation was chosen because it contains the maximum experimental tests. Figure 13 shows the experimental and simulated temperatures. Moreover, the estimation errors between experimental and simulated temperature are shown in Figure 14. The estimation errors were 0.14160, 0.10920, 0.06808, and 0.4012% for the first, second, third, and fourth tests, respectively. Figure 15 shows the temperature behavior of each evaporator tube in each test. Table 7 shows the $Re_{Onset,Tub}$, temperature results, and errors in each test of the simulation.

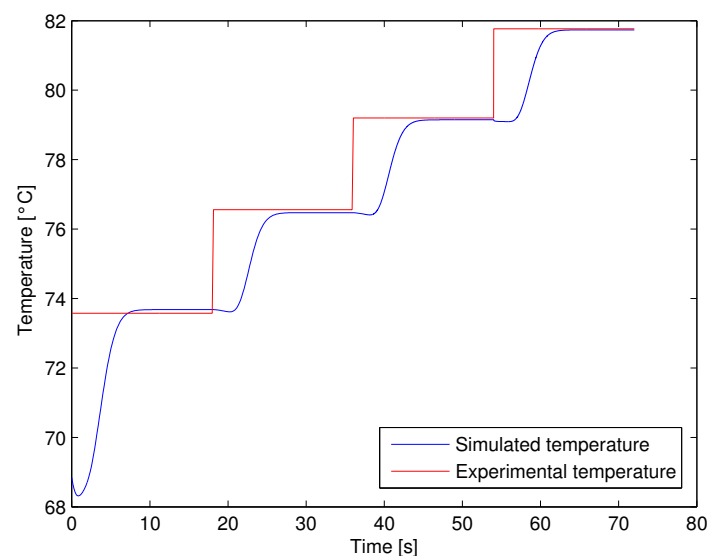


Figure 13. Experimental and simulated temperatures of the validation.

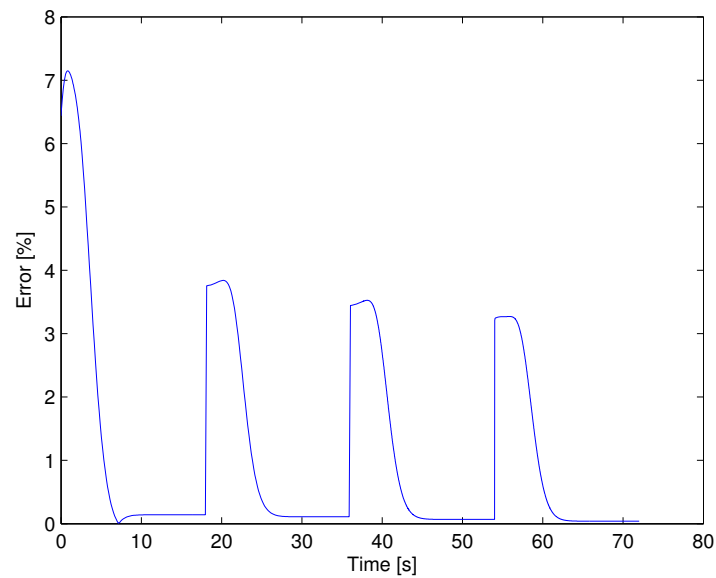


Figure 14. Error between experimental and simulated temperatures.

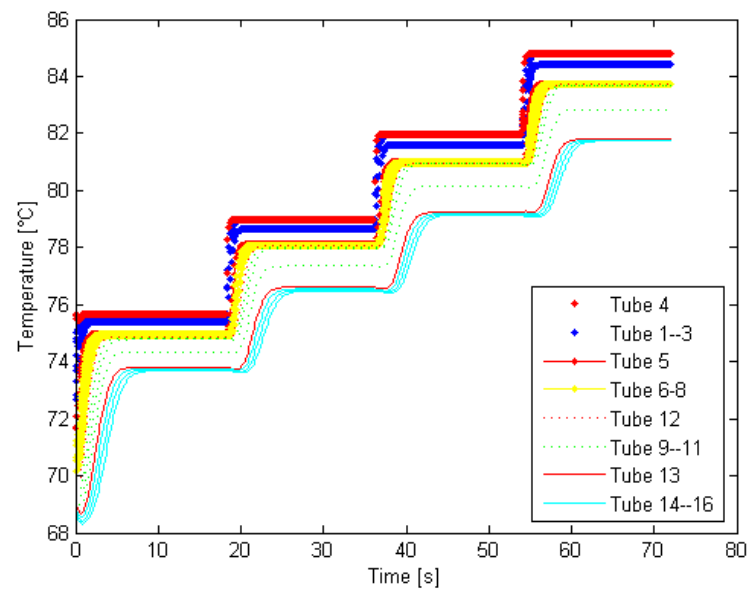


Figure 15. Behavior of the temperature of each tube.

Table 7. Validation results.

Simulation	Test Number	Re_{Onset}	T_{mExp} [°C]	T_{mSim} [°C]	$Error_{Tub}$ [%]
3	1	11.19	73.5761	73.6803	0.14160
	2	11.59	76.5561	76.4725	0.10920
	3	11.74	79.2009	79.1469	0.06808
	4	11.93	81.7683	81.7355	0.04012

3.3. Results of the Modeling of the Falling Film Evaporator with Nested Coils

The behavior of the falling film evaporator with nested coils is difficult to predict, and its analysis is complex because the heat source water flows in different directions, the decrease in the temperature gradients is different between the coils, and the size of the coils is different. Hence, a simulation was carried out to understand the behavior and detect some advantages and disadvantages of this evaporator configuration. The operating conditions used for this simulation correspond to the test with the highest falling film mass flow rate, which is test 2 of the simulation 2 shown in Table 4. The estimated value of $Re_{Onset} = 16.28$ obtained in Section 3.1 was used in the simulation to increase the reliability of the model results.

Figure 16 shows the temperature profile of the tube side along the helical evaporator according to the arrangement of the tubes and the flow direction of the heating water. The temperature enters through the bottom of the first coil, namely in tube 4. Therefore, the fluid in tube 4 has the maximum temperature, and from the tube 3 to 1, the temperature decreases. Subsequently, the fluid passes to the second coil and flows from the top to the bottom, namely it flows from tube 5 to tube 8. Thus, the temperature decreases from tube 5 to tube 8. Subsequently, the fluid passes to the third coil and flows from the bottom to the top, and the temperature decreases from tube 12 to 9. Finally, the heating water flows from the top to the bottom of the fourth coil, where the temperature decreases from tube 13 to 16.

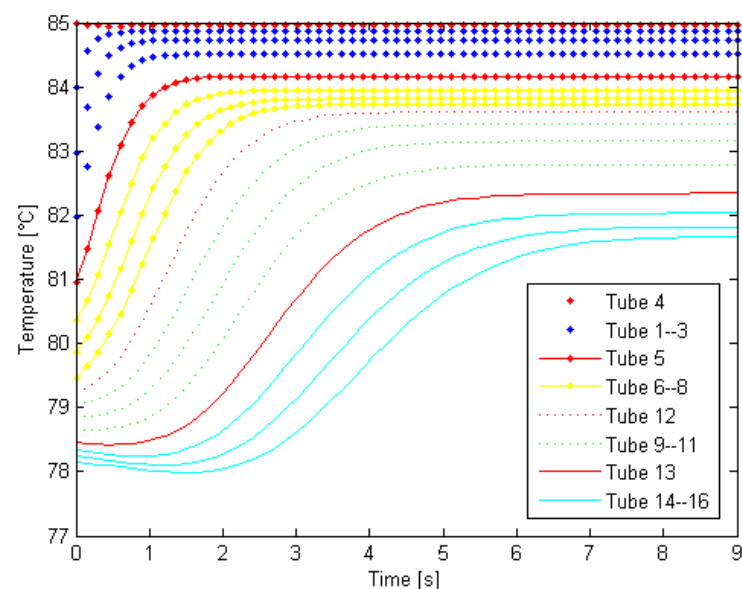


Figure 16. Temperature profile of the heat source.

An important parameter in falling film evaporators is the wetting efficiency because the heat transfer rate depends on it. Figure 17 shows the behavior of the wetting efficiency on the tubes. As shown in the figure, the wetting efficiency is maximum at the first level of all coils. This occurs because the mass flow rate and the Reynolds number are the same at the inlet for all coils. Additionally, the figure shows that the wetting efficiency decreases from level 1 to 4. This decrease is because less fluid flows on the down tubes due to the evaporation. Moreover, the wetting efficiency increases from coil 1 to 4 for each level. This increase is because the difference in temperature in the last coils is lower, causing a lower evaporation per transfer area.

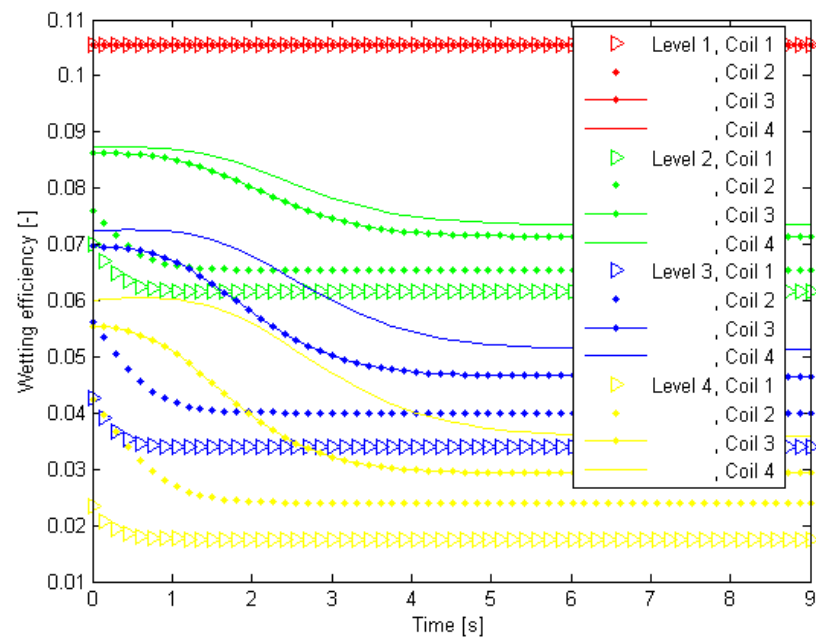


Figure 17. Wetting efficiency per tube.

Figure 18 shows the behavior of the Reynolds number at steady state. As the wetting efficiency, the Reynolds number decreases from level 1 to 4, and increases from coil 1 to 4.

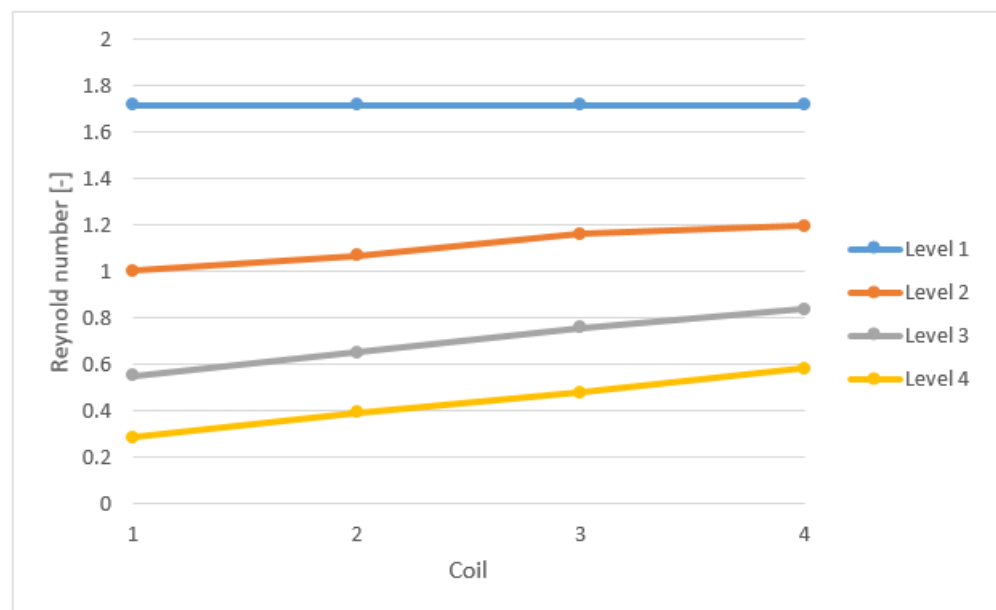


Figure 18. Reynolds number in each tube.

Figure 19 shows the heat transfer rate in each tube. As shown in the figure, the heat transfer rate decreases from level 1 to 4 in each coil as a consequence of the decrease in the wetting efficiency. Moreover, the heat transfer rate increases from coils 1 to 4 in each level due to the increase in the coil size.

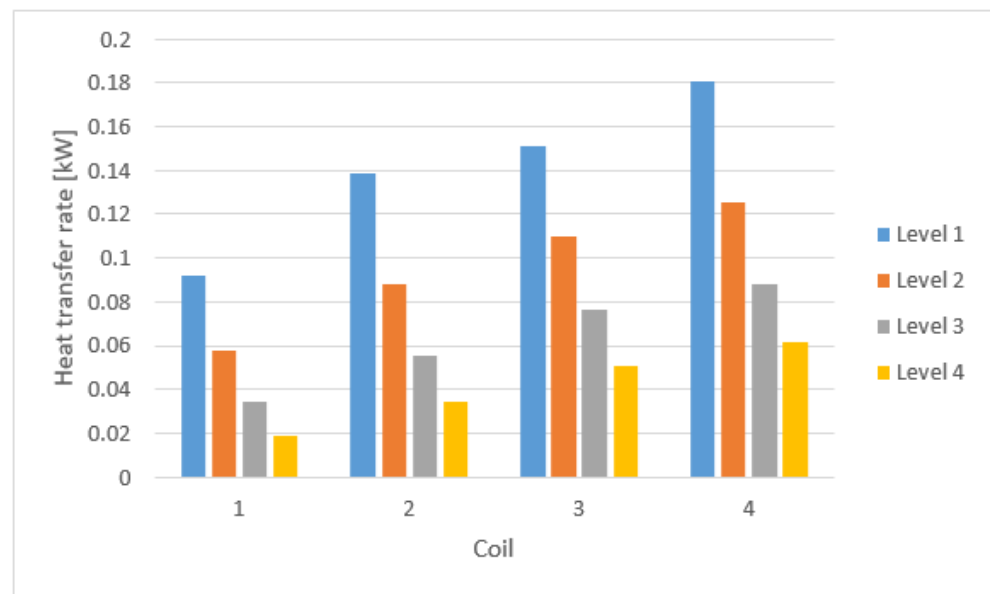


Figure 19. Heat transfer rate per tube.

Figure 20 shows heat transfer rates per level. The heat transfer rates of the tubes of levels 2, 3, and 4 are 67.92%, 45.33%, and 29.81% of the heat transfer rate of the tubes of level 1, respectively. Therefore, these results show that from level 3, increasing the number of levels is slightly useful. Figure 21 shows the heat transfer rates per coil. This figure shows that the tubes of coils 1, 2, and 3 transfer 199.18% of the heat transfer rate of the tubes of coil 4, which means coils 1, 2, and 3 transfer 0.9085 kW, whereas coil 4 presents 0.4561 kW. Similarly, coils 1 and 2 present a heat transfer rate of 133.59%, compared to the heat transfer rate of coil 3. Coil 1 presents a heat transfer rate of 63.83% compared to the heat transfer rate of coil 2. Therefore, using the space inside the coil significantly improves the heat transfer performance.

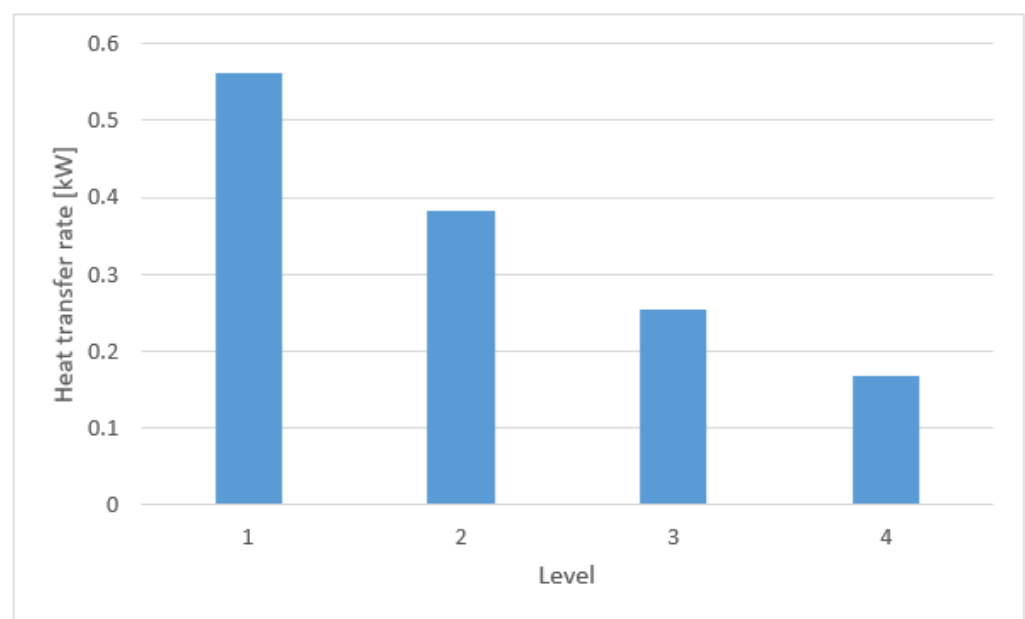


Figure 20. Heat transfer rate per level.

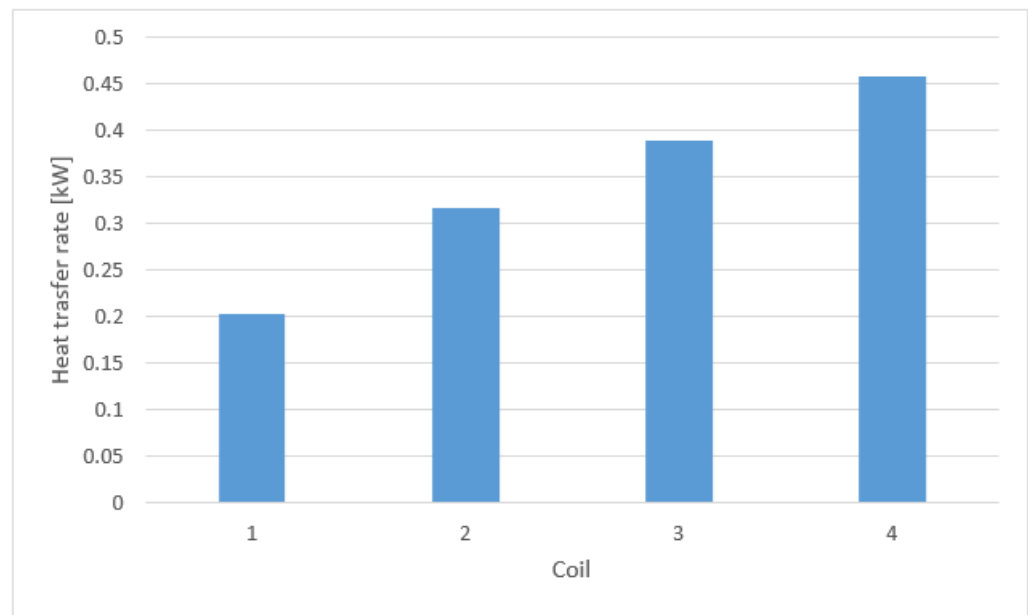


Figure 21. Heat transfer rate per coil.

3.4. Trend Analysis

The variables affecting the Re_{Onset} are not easy to determine because development of a well-planned experimental design is necessary for this purpose. However, some trends of the Re_{Onset} behavior concerning the temperature difference and the pressure were found in the present work.

Figure 22 shows that Re_{Onset} increases when the temperature difference increases. This behavior can occur because at higher temperature differences, evaporation occurs more easily, and it is more difficult to wet the tube. Consequently, the mass flow rate must be greater to wet the tubes fully. Therefore, Re_{Onset} increases.

Figure 23 shows that Re_{Onset} decreases when the pressure increases. This trend can occur because the falling film evaporates easier at lower pressure, making wetting difficult and requiring a higher mass flow rate to wet the tubes fully. Therefore, Re_{Onset} should be higher at lower pressure.

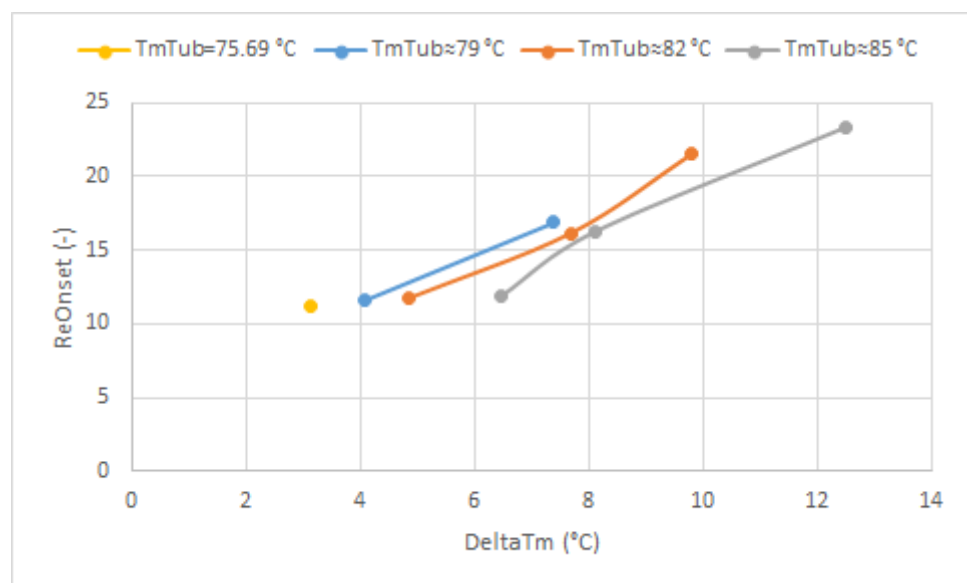


Figure 22. Re_{Onset} at different temperature differences.

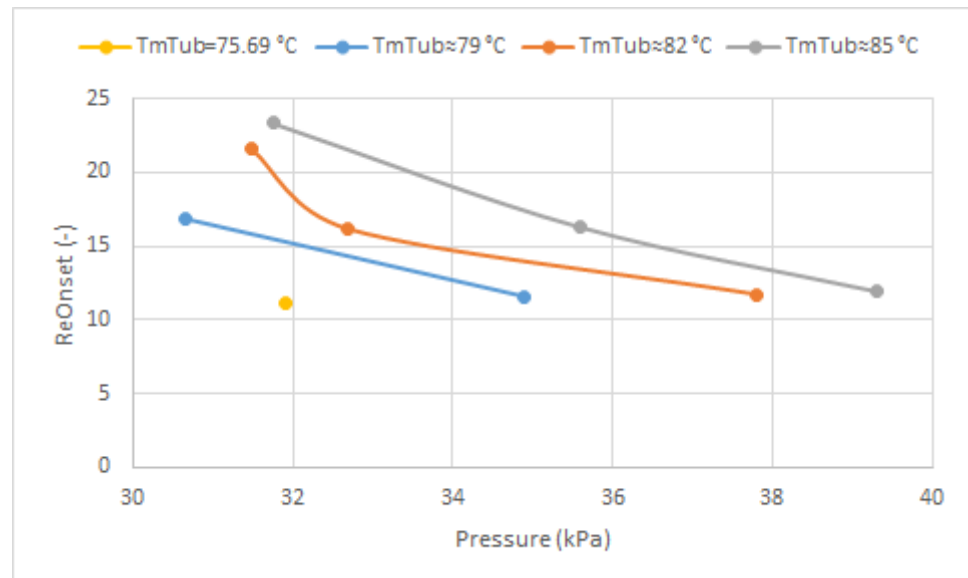


Figure 23. Re_{Onset} at different pressures.

4. Conclusions

This article presented the results of implementing a nonlinear adaptive observer to estimate the Re_{Onset} . The nonlinear model of the falling film evaporator of an absorption heat transformer was used to design the nonlinear observers. The results showed that by estimating the Re_{Onset} using an adaptive observer, the temperatures of the evaporator were calculated accurately regarding the experimental data, validating the estimation technique. The estimation temperature errors of the observer were between 0.00003% and 0.02815%. Finally, the temperature behavior, wetting efficiency, Reynolds number, and heat transfer rate were presented and analyzed. The estimated Re_{Onset} was used in the simulation to increase the reliability of the model results. The mathematical model shows that the heat transfer rates of the tubes of levels 2, 3, and 4 are 67.92%, 45.33%, and 29.81% of the heat transfer rate of the tubes of level 1. It also showed that the tubes of coils 1, 2, and 3 transfer 199.18% of the heat transfer rate of the tubes of coil 4. Therefore, using the space inside the coil significantly improves the heat transfer performance. The investigation presented in this work led to an opportunity gap in carrying out investigations to develop models and their validation using unknown parameter estimation. The parameter estimation increases the model reliability, which can aid in improving the performance and design of the heat exchangers. It is expected in future research to estimate the Re_{onset} parameter by using another adaptive observer to compare different estimation methods.

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Nomenclature

A_{Trn}	Transfer area (m ²)
C_p	Specific heat capacity (kJ/kg°C)
H	Specific enthalpy (kJ/kg)
M	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}_{Trn}$	Heat transfer rate (kW)
Re_{Flm}	Film Reynolds number, $Re_{Flm} = \frac{4\Gamma}{\mu_{Flm}}$, (–)
Re_{Onset}	Film breakdown onset Reynolds number (–)
t	Time (s)
T_m	Temperature (°C)
U	Overall heat transfer coefficient (kW/m ² °C)

Greeks

Γ	Liquid mass flow rate per unit length of tube, $\Gamma = \frac{\dot{m}_{Flm}^i}{2L}$, (kg/s·m)
ΔT	Temperature difference (°C)
η_{Wet}	Wetting efficiency (–)

Subscripts

Flm	Film side
Tub	Tube inside side
Vap	Vapor

Superscripts

i	Inlet
o	Outlet

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