1. Introduction

Global efforts to defossilize industrial production are transforming the chemical and process industry, shifting the focus to sustainable, resource-efficient, and environmentally friendly processes [1, 2]. At the same time, the demand for high quality products is increasing. These parallel developments call for highly flexible processes and innovative apparatus technologies [3]. Thermal separation processes play a crucial role in purifying products and recovering valuable components such as solvents, significantly influencing ecological and economic evaluations due to their high energy demands and their impact on the quality of the final product [4]. However, many conventional thermal separation methods are unsuitable for complex fluids, e.g., polymer solutions, with high viscosity, thermal instability, or tendencies toward fouling and scaling. In such systems, excessive thermal stress can cause decomposition or unwanted side reactions such as polymerization or degradation, thereby reducing product quality [5, 6]. To minimize thermal damage, operation at reduced pressures and narrow residence time distributions (RTDs) with low mean residence times are advantageous.

In this context, wiped film evaporators (WFEs) are an established type of apparatus that allows high heat transfer rates and low residence times with narrow RTDs [7]. Within a WFE, a rotating wiper system, consisting of rotor blades or flexible wipers, continuously redistributes a liquid film along the heated inner surface of the cylindrical evaporator body. This intensifies heat and mass transfer, preventing film stagnation and allowing the processing of even highly viscous or particle-containing fluids [8]. These features enable the recovery of valuable components from complex mixtures like industrial waste streams and the purification of heat-sensitive products such as pharmaceuticals [9, 10, 11, 12]. Beyond conventional separations, WFEs also offer promising perspectives for integrated processes such as continuous reactive distillation [13]. Consequently, WFEs can contribute to cost reductions and decrease the carbon footprint of chemical processes [14].

Reliable design and operation of WFEs require detailed knowledge of the flow phenomena within the liquid phase and their interaction with heat and mass transfer [15]. Previous investigations have focused on fluid dynamics [16, 17, 18], heat transfer behavior [19, 20, 21], or the impact of wiper geometry [17, 18, 22]. However, the results are mostly system-specific, lack scalability, and insufficiently consider the coupling of mechanical agitation, heat transfer and fluid dynamics. The large number of variables, including thermophysical properties, specific wiper designs, and operating parameters, further amplify the complexity of WFEs. Therefore, a thorough understanding of the interactions within WFEs is still limited. This leads to costly pilot experiments, oversized equipment, and hinders the use of WFEs for integrated processes. Consequently, the full potential of WFEs remains underutilized.

This work addresses this knowledge gap by investigating the morphology and flow behavior of the liquid under evaporation conditions in WFEs. Particular attention is placed on understanding how heat transfer influences fluid dynamics and the RTD, with the aim of optimizing process performance. The research focuses on a WFE equipped with roller wipers, combining experimental investigations with a mechanistic modeling approach to improve the general understanding of the system. The methodical framework is illustrated in Figure 1.1, which outlines the research objective, the use of the experimental data alongside the complementary modeling approach, and the outcome of this

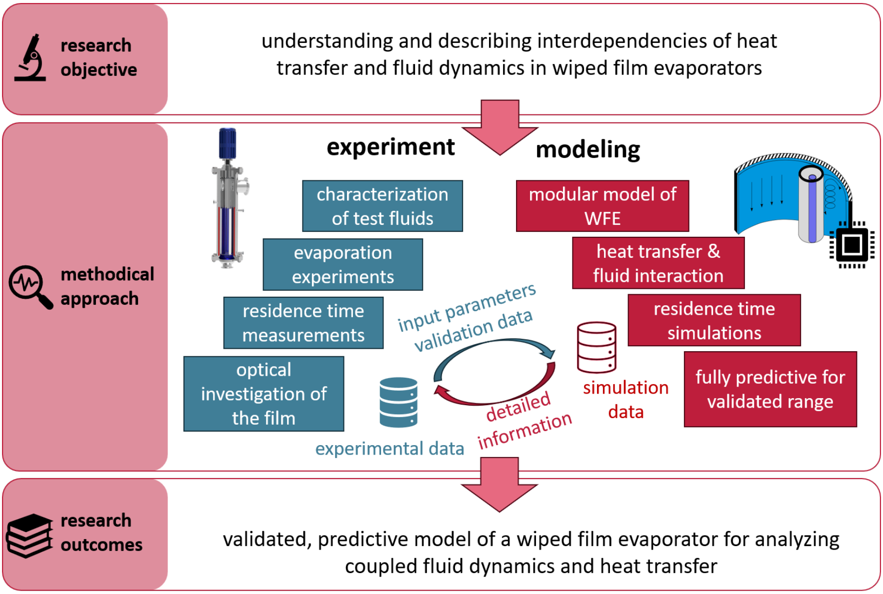

Figure 1.1.: Research objective, methodical approach and research outcomes of this dissertation.

research, resulting in improved knowledge and understanding of WFE.

To contextualize this study within the current state of research and highlight existing research gaps, key findings and correlations from the literature are critically reviewed and discussed in chapter 2.

For experimental characterization, RTDs during evaporation were measured in a laboratory-scale, steam-heated WFE made of stainless steel. The experimental procedure and the applied methodology are described in detail in chapter 3. These experimental data serve as the basis for the parameterization and validation of a modular model of the WFE. To ensure consistency and comparability, four reference fluids (diethylene glycol, isopropyl alcohol, decan-1-ol, and glycerol) were selected based on specific criteria, such as viscosity range, availability, and toxicity. The pure substances and their binary mixtures were subsequently analyzed with respect to their relevant thermophysical properties. The results of the reference system study, previously published in J. Chem. Eng. Data, 69, pp. 2927–2948, 10.1021/acs.jced.4c00152 are reprinted in chapter 4.

Diethylene glycol was selected as the primary reference system for comprehensive analysis during WFE operation. Alongside process data and RTD measurements, high-speed videos of the inner evaporator wall were recorded to capture film flow patterns and instabilities. The video data were evaluated in conjunction with experimental measurements in order to understand the effect of evaporation on fluid dynamics. These experimental results are reprinted in section 5.1 and were published in Chem. Eng. Res. Des. 218, pp. 341–349, 10.1016/j.cherd.2025.04.036.

The measured heat transfer coefficients are compared with established correlations in section 5.2, in which the influence of the operational parameters is estimated. For a more detailed assessment of the influence of temporary or permanent dewetting phenomena on heat transfer and residence time distribution, height-resolved image series are analyzed in section 5.3 and compared with experimental findings.

The experiments were complemented by comprehensive modeling of the entire apparatus, incorporating both heat transfer and fluid dynamics. To better understand the coupling of these processes, a detailed and modular model of the WFE was developed using Modelica. Initially, a fluid dynamic model was developed and calibrated to experimentally determined RTDs. This model included the gap width between the wiper and the inner wall as well as an empirical dead volume factor as fitting parameters. The model structure of the fluid dynamic model and the results of the simulations are presented in chapter 6, in which section 6.2 is an updated reprint of Chem. Eng. Res. Des. 161, pp. 115–124, 10.1016/j.cherd.2020.07.001.

The model was subsequently expanded to integrate heat transfer, resulting in a fully predictive model by reducing the degree of freedom of the WFE system. The simulation results are compared with the experimental data during evaporation, providing insight into the interactions of fluid dynamics and heat transfer processes. The segmental model structure taking into account heat transfer and its simulation results is shown and discussed in chapter 7 in wich section 7.1 is reprinted from a publication of Sep. Purif. Technol. 371, pp. 132840, 10.1016/j.seppur.2025.132840.

This combined approach enables a detailed evaluation of how evaporation influences fluid dynamics in WFE. Potential dewetting phenomena arising from film destabilization, decreased volume flow, or gas-liquid interactions can be assessed. In addition, the influence of important operating parameters such as rotational speed or superheat can be systematically analyzed and compared with experimental observations during evaporation. This not only improves the fundamental understanding of coupled thermal–hydrodynamic processes in WFEs, but also allows for targeted validation and future refinement of the developed model.

This thesis lays the groundwork for more effective design and operation of WFEs by combining experimental insights and a adaptable modeling framework. These advancements not only improve the economic and environmental performance of existing processes, but also open up new applications of WFEs.

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This dissertation is structured as a cumulative thesis. Parts of the work have already been published in peer-reviewed journals. The respective sections are clearly stated, and any changes from the original publications are indicated.

2. Theoretical Background

This chapter provides an overview of typical applications and the design of wiped film evaporators (WFEs), outlines the main factors that influence their performance, and discusses challenges associated with their operation. The current state of knowledge with regard to the flow and heat transfer behavior of WFEs is presented, including a comparative assessment of different investigations. Finally, the scope and objectives of this work in the context of the state–of–the–art are outlined.

2.1. Design and Use of Wiped Film Evaporators in Industrial Thermal Separation

Evaporation is a unit operation in which a fluid is (partially) transferred to the gas phase by transferring heat to a liquid at boiling temperature. It is used to concentrate liquid solutions as well as to separate homogeneous mixtures, in which the phase equilibrium leads to a composition difference between the gas and liquid phase. Despite the simplicity of the operation itself, a variety of different evaporator designs are used to ensure a high heat transfer coefficient and low investment. Low-cost options such as forced-circulation and thermosyphon reboilers are commonly used for various fluid systems but can harm products through thermal stress and are unsuitable for highly viscous fluids. An evaporator type providing high heat transfer coefficients yet having very low pressure losses is the falling film evaporator (FFE). In this apparatus, a free-falling film is formed along the surface of a heated wall. Although FFEs exhibit high heat transfer rates, their operation is often limited by film instability and dewetting effects caused by surface tension forces [27]. To overcome this limitation, WFEs can be used in which moving wiper systems redistribute the liquid film periodically.

2.1.1. Working Principle of Wiped Film Evaporators and Common Use Cases

WFEs operate on a working principle similar to that of FFEs. The design and operation mechanism of the WFEs are presented in Figure 2.1 and have been used for more than 75 years [28, 29]. The liquid feed is typically preheated to reach the boiling temperature of the mixture and distributed by a liquid distributor. The liquid is then continuously spread along the wall using a wiper system. The wall may be heated using electricity, a heating medium such as thermal oil or steam [7]. The vapor condenses in an external condenser. The sump is drained either by the wiper system or by gravity. Due to the wiper, the film is continuously renewed, allowing the processing of highly viscous fluids as well as film thicknesses that would cause film rupturing in FFEs [30]. The distribution of the liquid on the wall increases the turbulence and the heat transfer coefficient on the product side, while at the same time reducing the mean residence time of highly viscous fluids [6, 31]. Therefore, in the literature, residence times of less than 60 s are typically reported [32].

Due to the large free cross section, very small pressure losses can be realized along the height, allowing low process pressures down to 1 mbar and consequently reduced process temperatures, which ultimately minimize thermal stress on the fluids [33, 34]. WFEs can therefore be used in a variety of challenging process tasks. The most common uses cover the evaporation and purification

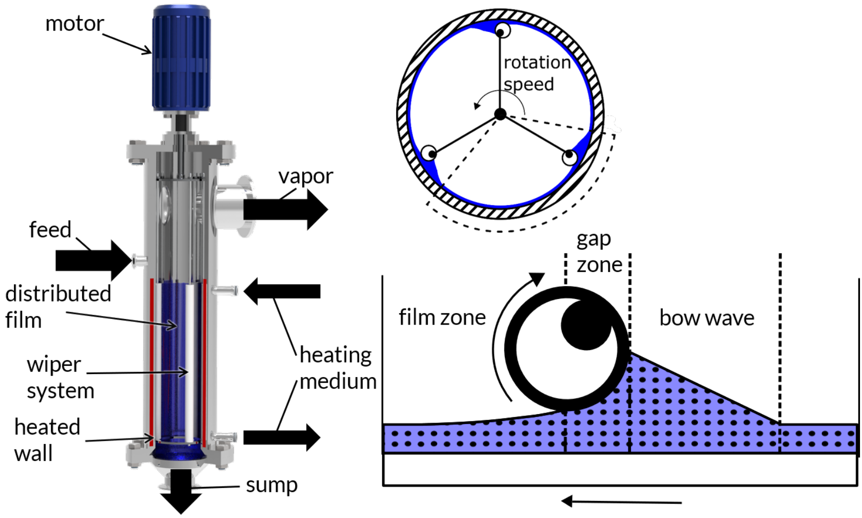

Figure 2.1.: Working principle of a wiped film evaporator, with the wiper system ensuring uniform film distribution. This leads to the formation of a bow wave zone in front of the wiper, a gap zone under the wiper and a free-falling film region.

of thermosensitive fluids, the recovery of solvents from highly viscous or foaming media, and the concentration of food [21]. WFEs have also gained attention for their use as a reactor in reactive distillation, because of their ability to achieve almost isothermal temperature profiles with very short residence times [13, 35, 36, 37]. Due to their numerous benefits compared to other types of evaporators, WFEs are utilized in various industries, such as pharmaceuticals, chemicals, and food processing, usually as one of the last refining steps [21].

If WFEs cannot achieve the necessary operating pressure, short-path evaporators can be used, which follow a similar working principle. As in the WFE, there is a mechanical wiper system that distributes the liquid on a heated wall, but the condenser in the short path evaporator is located inside [38]. This allows the pressure in short-path evaporators to be reduced down to $p_{\mathrm{abs}} = 10^{-3}$ mbar [34]. At such low pressures, molecular distillation occurs, which means that the fluid evaporates without any signs of boiling [39]. However, short-path evaporators follow the same physical principles as WFEs in terms of influencing variables, heat transfer, and fluid dynamics, as described in the following.

2.1.2. Factors Affecting Process Performance

The operation of WFEs depends on the geometric dimensions and design of the apparatus itself, its material and wiper system used, the processed mixtures and their thermophysical properties, as well as the operational parameters that influence both heat transfer and fluid dynamics in WFEs [31]. An overview of the main influencing variables is shown in Table 2.1 [40]. Understanding the interactions between geometric and operational parameters, as well as the thermophysical properties

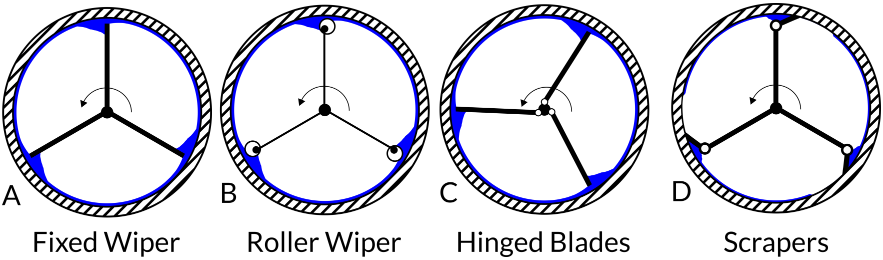

Figure 2.2.: Overview of different wiper types commonly applied in wiped film evaporators (adapted from [40]).

of the fluids, is essential to predict the operational behavior of WFEs. These interactions influence heat transfer, wettability, and fluid dynamics. Although there have been numerous comprehensive studies on these parameters, the multitude of influencing factors makes it challenging to transfer the research findings to other applications without restrictions [39, 41, 42]. The influence of the most relevant input parameters is explained in detail in the following section.

2.1.2.1. Equipment Specific Parameters

As equipment specific parameters the wiper design, the number of wiper elements, the geometry of the inner and outer shell as well as general specifications such as the sealing material or the liquid distributor can be defined. The geometric dimensions directly interact with the operational parameters, such as the wiping frequency or the surface peripheral load. Therefore, they also define the maximum and minimum throughput. The diameter of the device, its length, the thickness, as well as the material (glass/metal) of the wall, and its thermal conductivity influence the heat and mass transfer [43, 44]. The wiper system, that is directly in contact with the liquid film, has a significant impact on the fluid dynamics that forms and can be selected individually depending on the application. Figure 2.2 provides an overview of different common wiper types. Generally, a distinction can be made between wipers with a fixed wall distance, with a movable wiper system, and those with a very small wall distance (the so-called scrapers) [17]. With fixed wiper systems (Figure 2.2 A) - also known as Sambay type - the gap width is fixed. Those wipers can transmit high shear rates and induce turbulence in the medium [45, 46]. This design is therefore often chosen for systems that tend to

Table 2.1.: Geometrical, thermophysical and operational parameters influencing the operation of WFEs (adapted from [40]).

equipment specific	fluid properties	operational
wiper design	viscosity	wiper speed
equipment geometry	density	temperature utility
wall material	vapor pressure	peripheral load
design utility side	surface tension	process pressure
seals	temperature sensitivity	feed temperature
liquid distributors	phase equilibria	
	fouling, foaming, etc.	

foul or for highly viscous fluids up to 2000 Pa·s such as polymer solutions, as the gap width remains independent of the viscosity [16]. Fixed wipers can lead to an increase in the mean thickness of the film and residence time due to the deceleration of the liquid on the wiper and an overall increase in hold-up volume compared to FFEs [32]. This effect persists even if the equivalent film thickness of the falling film is less than the gap width between the wiper element and the wall. As surface waves can reach amplitudes of two to six times the average film thickness, the wiper can still induce a pronounced bow wave under these conditions [32, 47]. However, at high evaporation ratios, the bow wave may be significantly diminished as a result of the decreased liquid volume. This can result in film thicknesses well below the wiper gap, thereby leaving the wiper system without any effect [48].
As an alternative, movable wiper elements or hinged blades can be used (Figure 2.2 B + C). Here, the wiper elements are pressed onto the wall of the apparatus by means of centrifugal forces or elastic springs [49, 50]. The wiper gap is created as a result of a balance of fluid dynamic and centrifugal forces, which ensures continuous wetting of the apparatus wall [50, 51]. Thus, thin films up to 0.6 mm are formed, and even suspensions or mixtures in which salts can precipitate can be processed [33].
Scraper systems (Figure 2.2 D) can be used for very viscous substances or substance systems with a strong fouling tendency [30]. Next to the wiper type itself, the wiper geometry, the number of wiper elements, and their arrangement can influence the operating behavior [52].
Although usually WFEs are constructed in a tubular shape, special forms include conical design and horizontal layout. In a conical evaporator design (design Sako), the width of the gap can be set precisely by adjusting the height and the risk of film rupturing is reduced [53, 54]. Although it is more difficult to manufacture, it allows for the evaporation of the liquid while maintaining a minimum peripheral load. Additional components such as retaining rings showed a significant increase in the mean liquid hold-up, which ensures wetting and greatly increases the mean residence time of the fluid [32]. A horizontal layout is mostly used for drying processes, ensuring the transport of the liquid by choosing a wiper system that directs the flow towards the evaporator exit. More complex designs are commonly implemented on an industrial scale. For example, a segmented heating jacket supports precise temperature control [55]. Furthermore, a height-dependent wiper system can be used to vary the wiper frequency in different segments [56], which improves the flexibility of the process.

2.1.2.2. Fluid Properties

The fluid properties are mostly predefined by the mixture to be purified. The fluid dynamics and heat transfer are influenced by the viscosity η, density ρ, surface tension γ, diffusion coefficient D_{diff}, thermal conductivity λ, the boiling temperature T_b and phase equilibria that occur.
In WFEs, fluids ranging from aqueous solutions to polymer melts, with viscosities of up to 2000 Pa·s, are processed [16, 57, 58]. Highly viscous fluids often exhibit non-Newtonian behavior in terms of shear rate- and time-dependent properties [16]. Due to the wide range of viscosities and fluid types processed in WFEs, the resulting flow morphologies can vary significantly (see subsection 2.2.1) [6, 59]. For fluids with high viscosities, laminar flow regimes may occur, leading to reduced heat and mass transfer as well as increased mean residence time [6, 39, 60, 61].
The transport properties of thermal conductivity λ and diffusion coefficient D_{diff} play a crucial role

in heat and mass transfer, especially for highly viscous fluids. Based on penetration theory, which is explained in more detail in subsection 2.2.2, it can be assumed that periodical mixing of the film and the bow wave lead to transient, diffusive heat and mass transfer within the film [62, 63], which depends on the transport properties of the fluid.

The gravimetric flow as well as the impulse transport within the liquid film is influenced by the density of the liquid. An increase in fluid density tends to increase the heat transfer coefficient and the mass flows that occur, reducing the mean residence time in the apparatus [22, 64].

Surface and interfacial phenomena occur in the apparatus due to evaporation from thin layers. This can lead to rupturing of the film, especially under evaporation conditions and at lower peripheral loads [65]. In order to properly understand these phenomena, it is essential not only to evaluate the surface tension but also to include the dynamic contact angle, given its important role in dynamic dewetting phenomena [66, 67]. The underlying mechanisms of the formation of thin films, their stability and the influence of evaporation are discussed in more detail in subsection 2.2.3. The local boiling temperature results from the phase equilibria of the individual components of the system and their vapor pressures. This can lead to a significant change in the fluid temperature and thus the temperature-dependent fluid properties along the evaporator height, particularly in the case of wide-boiling mixtures [68].

2.1.2.3. Operational Parameters

The variables that can be controlled to influence the process are typically the operational parameters. They allow the flexible adaption of one WFE to different processes. The boiling temperature can be set via the process pressure. Besides the process pressure, the feed mass flow $\dot{m}_F$ significantly determines which flow velocities and liquid hold-ups occur in the evaporator. To achieve a better comparability of the results of different authors, it is often beneficial to use the peripheral load Γ instead of the mass flow $\dot{m}$, which may be calculated according to Equation 2.1.

$$\Gamma = \frac{\dot{m}}{\rho \cdot \pi \cdot d_r} = \frac{\dot{V}}{\pi \cdot d_r} \tag{2.1}$$

While mass flow and operating pressure are also varied in other devices, the wiper speed is an additional, WFE-specific process variable. As shown in section 2.2, the wiper speed influences both heat transfer and residence time, whereby no further change in heat transfer and fluid dynamics can be expected above a process-specific wiper speed [19, 69]. In particular, during scale-up, the motor frequency n is less important than the wiper speed w and the wiper frequency f_{wiper}, which result from Equation 2.2.

$$f_{\text{wiper}} = n \cdot N_B = \frac{w}{\pi \cdot d_r} \cdot N_B \tag{2.2}$$

Assuming an almost constant heat transfer coefficient, the heat flow can be adjusted via the superheat ΔT (see Equation 2.3). The superheat is adjusted by changing the temperature of the utility side T_{util}. During evaporation, the process temperature T_p is equal to the boiling temperature of the liquid.

$$\Delta T = T_{\text{util}} - T_p \tag{2.3}$$

In cases involving mixtures, high evaporation ratios, or feeds below the boiling temperature, it is crucial to consider the temperature change along the height of the evaporator. This can be achieved by calculating an appropriate mean superheat or conducting a segmental simulation [68].

2.2. Heat Transfer Characteristics and Flow Behavior in Wiped Film Evaporators

The different influencing parameters described in subsection 2.1.2 impact heat transfer and fluid dynamics. In order to better understand the dependencies of the operating behavior on these variables, the current state of knowledge on the most important influencing parameters is summarized below. Fluid dynamics is initially discussed in subsection 2.2.1, followed by a presentation of various mechanistic and empirical methods to describe heat transfer in subsection 2.2.2. Finally, subsection 2.2.3 briefly summarizes the current state of knowledge on the stability of thin films under adiabatic and evaporation conditions.

2.2.1. Flow Regimes and Their Effect on Fluid Dynamics

The fluid dynamics of liquid and gas flows in WFEs is critically important to characterize the flow behavior within these devices. Local velocity distributions provide information about the type of flow (laminar/turbulent) and the RTD. Indicating the mixing efficiency between different areas, these factors are fundamental for further considerations of mass and heat transport. An understanding of liquid distributions during operation is also essential for the transferability of processes and the optimization of a WFE as an apparatus.

2.2.1.1. Fluid Dynamics without Evaporation

The flow in the vertical WFE is influenced by both gravity and the wiper movement, resulting in the overall spiral downward fluid movement shown in Figure 2.3 [70]. In the feed area of the liquid, the wiper elements engage in the film and accumulate the liquid forming a bow wave in front of the wiper [44]. The accumulation of the liquid results in a rotational flow in the bow wave, which is usually turbulent, but can also be laminar for high values of the viscosity and low rotor speed [16, 60]. At high wiper speeds, secondary vortices can be induced in the bow wave [52]. The resulting convective mixing processes increase heat and mass transfer [70].
For a more precise analysis, the flow is usually divided into the three zones bow wave, gap zone and film zone as shown in Figure 2.4, which are described separately [25, 71, 72].

2.2.1.1.1. Bow Wave As the liquid builds up in front of the wiper, a bow wave forms in which convective mixing is increased due to increased turbulence. The shape of the bow wave varies between wedge-shaped and circular geometries depending on the set operating conditions [52]. A vortex forms in the bow wave, which induces a secondary vortex with increasing Reynolds numbers [44, 73, 74, 75]. The resulting vortices increase the mass transfer between the bow wave and the film [45]. The higher turbulence also increases heat transfer significantly [76]. However, with low Reynolds