e-ISSN: 2149-4584

Erzincan University Journal of Science and Technology

EJSAT 2026, 19 (1) 179-193

Research Article

Experimental Investigation of The Transition Process with Single-Phase and Two-Phase Flow Regions in Horizontal Pipes in Terms of Heat Transfer

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Received: 15/05/2025, **Revised:** 08/12/2025 **Accepted:** 22/12/2025, **Published:** 30/03/2026

Abstract

In this study, the effects of the transition from single-phase (liquid) flow to two-phase (liquid-vapor) flow on heat transfer were experimentally investigated in a horizontal pipe flow system. The experiments were conducted under constant heat input (24 kW) and constant system pressure (7.5 bar), by systematically reducing the mass flow rate. In the single-phase flow regime, heat transfer is primarily governed by forced convection mechanisms. However, upon reaching the fluid saturation temperature and the onset of evaporation, significant increases in heat transfer coefficient were observed in the two-phase region due to complex phase-change-related phenomena such as vapor bubble formation, interfacial movements, and condensation. Variations in the Nusselt number within this transition region, the onset of evaporation, and the characteristics of transitional regimes were analyzed in detail. Furthermore, the location and width of the transition zone were determined experimentally, highlighting its critical role in thermal performance. The results showed an average increase of 11.95% in the Experimental Nusselt number, indicating an improvement in heat transfer performance. The findings provide valuable engineering data to support more efficient designs of thermal systems such as evaporators and heat exchangers.

Keywords: two-phase flow, single-phase flow, heat transfer, pressure drop

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Yatay Borularda Tek Fazlı Ve İki Fazlı Akış Bölgeleri İle Geçiş Sürecinin Isı Transferi Açısından Deneysel İncelenmesi

Öz

Bu çalışmada, yatay bir boru içerisinde gerçekleşen iki fazlı akış sisteminde, akışın tek fazlı (sıvı) rejimden iki fazlı (sıvı-buhar) rejime geçişinin ısı transferi üzerindeki etkileri deneysel olarak incelenmiştir. Deneyler, sabit ısı girdisi (24 kW) ve sabit sistem basıncı (7.5 bar) altında, yalnızca kütlesel debinin farklı seviyelere düşürülmesiyle gerçekleştirilmiştir. Tek fazlı akış rejiminde ısı transferi esas olarak zorlanmış taşınım mekanizmalarıyla sınırlıyken; akışkan doyma sıcaklığına ulaşarak buharlaşmaya başlamasıyla birlikte, iki fazlı bölgede buhar kabarcığı oluşumu, ara yüzey hareketleri ve yoğuşma gibi faz değişimiyle ilişkili karmaşık fenomenlerin etkisiyle ısı transfer katsayısında belirgin artışlar gözlemlenmiştir. Bu geçiş bölgesinde Nusselt sayısındaki değişim, buharlaşma başlangıç noktası ve geçiş rejimlerinin özellikleri ayrıntılı olarak değerlendirilmiştir. Ayrıca, geçiş bölgesinin yeri ve genişliği deneysel verilerle belirlenmiş, bu bölgenin ısı transfer performansı açısından taşıdığı kritik rol vurgulanmıştır. Sonuçlar, Deneysel Nusselt sayısı ortalama %11,95 artış göstermiş ve bu durum ısı transferi performansının iyileştiğini ortaya koymuştur. Elde edilen sonuçlar, buharlaştırıcılar ve ısı değiştiriciler gibi termal sistemlerin daha verimli tasarlanmasına katkı sağlayacak nitelikte mühendislik verileri sunmaktadır.

Anahtar Kelimeler: iki fazlı akış, tek fazlı akış, ısı transferi, basınç düşümü

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Cite this Article: Erzincan University Journal of Science and Technology 2026, 19(1) 179-193. https://doi.org/10.18185/erzifbed.1699165

1. Introduction

Heat transfer is a physical process that forms the basis of thermal engineering applications, and in many industrial systems it shows significant variations during the transition of the fluid from one phase to another. Especially in two-phase flow systems, the regions where the flow transitions from a single-phase to two-phase structure stand out as critical regions where both the heat transfer coefficient and the flow regime change abruptly. This transition is usually defined by the onset of nucleation at the “onset of nucleate boiling” (ONB) point, where vapor bubbles form for the first time and the convective heat transfer mechanism becomes complex with the evaporation effect. While heat transfer in single-phase flow is determined by forced convection, two-phase flow exhibits a higher but unpredictable heat transfer performance due to vapor bubble formation, surface tension, bubble dynamics and vapor-liquid interface interactions. Therefore, the thermal characterization of the two-phase transition region and the experimental demonstration of the heat transfer changes in this region are critical both for scientific knowledge and for the design of heat exchangers, evaporators and cooling systems.

Heat transfer in single-phase flow is usually studied in systems where liquids or gases move in a single phase. Microchannel heat sinks are widely used in such systems and heat transfer performance can be improved by different manifold arrangements. For example, ZU and HU type manifolds are recommended for single-phase heat transfer applications with low thermal resistance and pressure drop [1]. Also, in flows exiting cross-shaped jets, lower surface temperatures have been observed in regions of high fluid velocities, which enhances convective heat transfer [2]. In single-phase flows, heat transfer coefficients are primarily affected by the flow velocity and the hydraulic diameter of the channel. Higher velocities increase turbulence, which increases the Nusselt number and thus the heat transfer coefficient [3]. In single-phase flow, pressure drop and heat transfer have a simpler structure. Pressure drop in single-phase flow is usually caused by factors such as friction, gravity and acceleration. In such flows, a well-planned piping layout and appropriate pipe material selection can reduce pressure drop and reduce operating costs [4].

In two-phase flow systems, heat transfer is analysed when liquid and gas phases coexist. The addition of the gas phase to the liquid can significantly increase the heat transfer coefficient [5]. In microchannel heat sinks, heat transfer coefficients in two-phase flow increase as vapour quality and mass flow increase [6]. The heat transfer properties of gas-liquid mixtures can be described by parameters such as Nusselt number and friction factor in different geometrical arrangements [7]. Two-phase flows can exhibit various regimes (such as bubbling, slug boiling, annular) that affect heat transfer. The presence of vapour bubbles increases heat transfer due to the latent heat of vaporisation, which results in higher heat transfer coefficients compared to single-phase flows [8]. Two-phase flow causes a non-linear increase in pressure drop with increasing vapour quality and mass flow, as seen in experiments with adiabatic tubes [9]. The pressure drop in such flows is usually greater than in single-phase flow due to the complex interactions between the phases. Increased pressure drop can significantly affect system design, especially in areas such as power generation and chemical processing. Understanding the details of two-phase pressure drop is vital to optimising equipment and ensuring efficient operation.

There are distinct differences between single-phase and two-phase flows. Two-phase flows generally have higher heat transfer coefficients, which is particularly advantageous for improving heat transfer in microchannel systems [10]. However, two-phase flows can often lead to greater pressure drop [6]. In two-phase flows, factors such as phase change and flow regime mapping can greatly affect heat transfer performance [11]. Although two-phase flows generally exhibit superior heat transfer properties compared to single-phase flows, the complexity of flow patterns and phase interactions can lead to variable results. For example, the presence of Taylor bubbles can reduce the efficiency of heat transfer under certain conditions [12-13]. Single-phase flows benefit from higher velocities with increased turbulence, while two-phase flows benefit from latent heat effects and may be more efficient under certain conditions. However, the complexity of two-phase dynamics can create challenges in maintaining optimal heat transfer performance.

The region where the phase transition begins usually occurs when the critical heat flux or temperature value is reached. At this point, vapour bubbles begin to form inside the pipe and the character of the flow changes. Experimental studies show that this transition leads to a sudden increase in the heat transfer coefficient and changes in the temperature distribution. The transition from single-phase to two-phase causes a significant increase in heat transfer and this transition zone can be experimentally determined by temperature and pressure changes. In addition, the temperature distribution becomes more homogeneous in two-phase flow and temperature fluctuations are reduced. These findings suggest that the single-phase to two-phase transition and the separation of this transition region in experimental studies with water in a horizontal stainless steel pipe are critical for heat transfer and should be considered in system design [14-17].

Chen (1966) is a classical approach that considers both nucleation and surface boiling effects of heat transfer in the one-phase to two-phase transition region [18]. This model is in good agreement with experimental data. The model developed by Chen is used to calculate the heat transfer coefficient in the transition zone by combining Dittus-Boelter and Cooper correlations. In his study, Hewitt (1978) discusses the experimental methods used to determine the transition zone in two-phase flows [19]. It is emphasised that the transition from one phase to two phases should be examined in terms of pressure drop and phase separation as well as heat transfer. Kandlikar, (2002) explains the basic mechanisms of boiling and two-phase flow in minichannels [20]. He proposes a comprehensive model explaining the reasons for the increase in the heat transfer coefficient in the transition from one phase to two phases. Kandlikar (2004) analysed in detail how two-phase flows, especially the boiling process, take place in microscale channels [21]. Sudden increases in the local heat transfer coefficient were observed during the transition from one phase to two phases. He emphasises that the heat transfer coefficient increases abruptly at ONB (the point where nucleation starts) and this increase depends on the flow regime, surface condition and fluid properties. Kandlikar's Correlation provides parameters specific to two-phase flow, taking into account the effects of surface tension and Reynolds number. Thome (2004) focuses on two-phase boiling in microchannels and describes in detail the heat transfer changes that occur in transition zones. He emphasises that sudden changes in the heat transfer coefficient can occur with the formation and growth of vapour bubbles [22]. Thome (2004) provides comprehensive information on the classification of flow regimes in two-phase flow and their effects on heat transfer [23]. The heat transfer coefficient shows significant changes in the transition of the flow to different regimes such as surface evaporation, nucleation boiling and vapour film formation. The transition of the flow to the superficial evaporation or nucleation boiling regime causes sudden jumps in heat transfer performance. In his experimental study, Bediako (2022) investigated the transition of R134a fluid from the subcooled liquid region to the superheated vapour region in horizontal straight stainless steel tubes [24]. The study measured local heat transfer coefficients and frictional pressure drops under low heat fluxes (4.6-8.5 kW/m^2) and mass fluxes (200-300 kg/m^{2}s). The vapour quality varied between -0.1 and 1.2. The results showed that the heat transfer coefficient increases with vapour quality and there are significant changes in the transition zone. Zhang, Z. et al. (2025) Flow regimes were observed with a high-speed camera and heat transfer coefficients in each regime were measured [25]. Heat transfer increases and decreases caused by regime transitions were characterised. However, the spatial extent of the transition region, the precise determination of the point where the transition starts, and the local heat transfer characteristics in this region are still open research areas.

In two-phase flow analyses, this basic knowledge and correlations of single-phase flow play an important role. In areas such as determination of local heat transfer coefficients, understanding of phase change mechanisms, analysis of phenomena such as critical heat flux and boiling crisis, and microchannel and nanofluidic applications, single-phase flow knowledge provides a reference point for modelling and optimisation of two-phase systems. Extensive experimental and numerical studies in the literature have provided a solid theoretical foundation for two-phase flow research by investigating in detail the basic principles of single-phase heat transfer and its behaviour under different conditions. Therefore, a rigorous study of the heat transfer characteristics of single-phase flow is necessary to understand and develop heat transfer mechanisms in two-phase flow systems.

In this study, the two-phase transition of a single-phase flow in a horizontal pipe is investigated experimentally. Under different flow rates and heat input conditions, the heat transfer characteristics at the vaporisation starting point and in the transition region surrounding this point are analysed. In this context, the variation of the Nusselt number due to the phase transition and the effect of the transition on the heat transfer performance were evaluated. The results obtained are expected to contribute to the understanding of two-phase heat transfer mechanisms and more efficient design of related systems.

2. Material and Methods

Two-phase Flow

The experimental setup was designed to investigate three major types of dynamic instabilities in boiling systems: pressure drop type, density wave type, and thermal oscillations. A schematic representation of the setup is provided in Figure 1. This study specifically examines the effects of mass flow rate, under constant inlet temperature conditions, on both single-phase and two-phase flow instabilities. The experimental system is composed of three main sections: the fluid supply section, the test section, and the fluid recovery section. Liquid water enters the circular test pipe from the supply section and gradually transforms into a liquid–vapor mixture as it absorbs heat through the pipe walls. By the end of the test section, the fluid reaches an almost completely vapor phase and is then directed to the recovery section for condensation and recirculation [26–29].

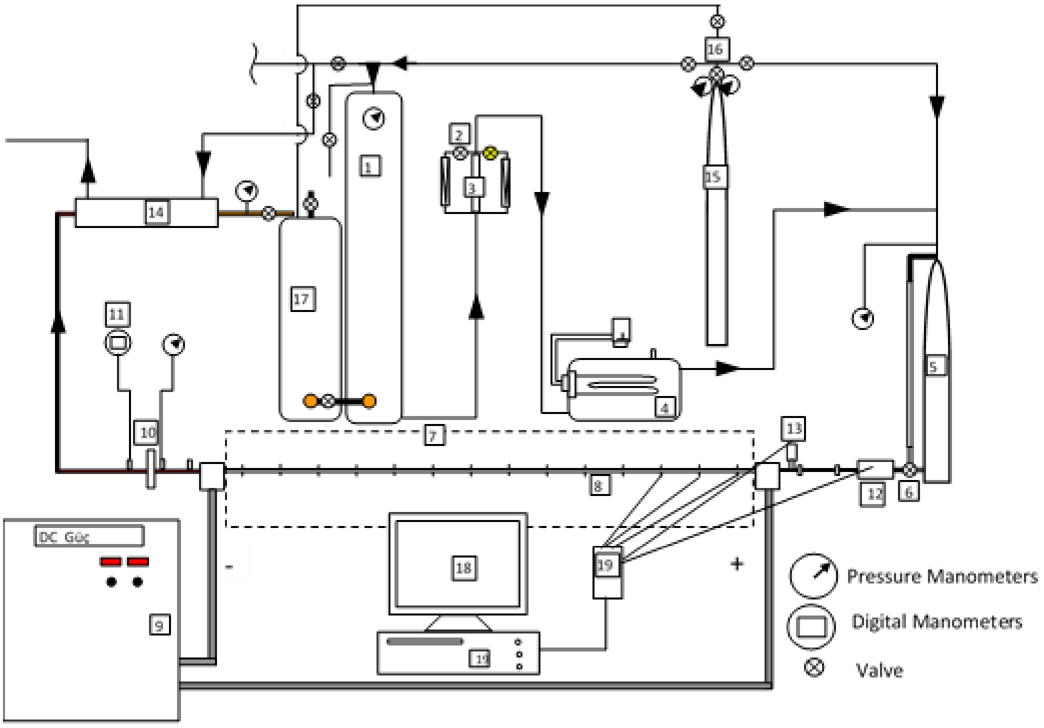

Figure 1. Two-phase flow test system and system components

The experimental setup, schematically shown in Figure 1, consists of three main sections: the fluid supply section, the test section, and the fluid recovery section.

- *In the fluid supply section*, water is stored in the main supply tank (1) and regulated via a flow control valve (2) and a flowmeter (3). A heat exchanger (4) ensures the fluid enters the system at the desired initial temperature.
- *The test section* comprises a surge tank (5), an inlet fluid control valve (6), a test plenum (7), and the test tube (8), which is heated using a DC power supply (9). Flow control at the exit is managed by an exit restriction (10). The test section is instrumented with a digital manometer (11), a turbine flowmeter (12), and a pressure transducer (13) to measure pressure drop and flow rate accurately.
- *In the fluid recovery section*, the vapor-phase fluid is condensed in a condenser (14), and pressure regulation is maintained by a nitrogen tank (15) and regulator (16). The recovered fluid is collected in a storage tank (17) and monitored through a PC interface (18) connected via a PC-Lab data acquisition card (19).

This configuration enables precise control and monitoring of fluid dynamics and thermal behavior under both single-phase and two-phase flow conditions.

The experiments were carried out under constant heat input (24 kW), system pressure (7.5 bar) and outlet restriction (diameter ratio 0.448). The initial flow rate was set at 380 l/h and the flow rate was gradually reduced at intervals of about 20-50 l/h to observe the transition from single-phase to two-phase flow. The lowest flow rate was set at approximately 110 l/h, and experiments were not carried out at lower flow rates due to the risk of combustion. At the beginning of the experiments, the main tank was pressurised with high pressure nitrogen gas and the system pressure was adjusted by the pressure regulator on the nitrogen cylinder. In the experiments, the expansion tank was pressurised with nitrogen gas to create a constant compressible volume. The water level in the tank was controlled by a transparent tube gauge.

In both types of experiments, the initial flow rate was set to 7.5 bar and the inlet temperature of the water was controlled by a digital thermostat. The cooling water was directed to the condenser and constant heat was applied through the pipe wall with a DC power supply. When the system was operated and reached steady state, no change in surface temperatures greater than 0.5°C was observed, indicating that there was no change with time. Then, measurements were taken and the same process was repeated for the determined flow rates.

In the experiments, rapid changes in pressure and water level in the expansion tank indicated the onset of oscillations. The volumetric flow rate was reduced until it reached 110 l/h and pressure drop type oscillations were observed. As the mass flow rate decreased, wall temperatures were carefully monitored to ensure that thermal oscillations occurred. Aroonrat, and Wongwises [30] determined the relevant parameters using Equations 1, 2 and 3 and compared with the relevant literature in Equation 4 and Equation 5.

$$\mathrm{Nu} = \frac{h_{avg} D_i}{k_l} \tag{1}$$

$$f_{TP} = \frac{\Delta P_F \rho_l D_i^3}{2\mathrm{Re}_{eq}^2 \mu_l^2 L} \tag{2}$$

$$\mathrm{Re}_{eq} = \frac{G D_i}{\mu_l}\left((1 - x_{avg}) + x_{avg}\sqrt{\frac{\rho_l}{\rho_g}}\right) \tag{3}$$

Colburn Correlation;

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \tag{4}$$

Petukhov Correlation;

$$\mathrm{Nu} = \frac{(f/8)\mathrm{RePr}}{1.07 + 12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3} - 1)} \text{for} 10^4 < \mathrm{Re} < 5x10^6 \tag{5}$$

3. Results and Discussion

In this study, heat transfer in a two-phase flow system is investigated and the heat transfer characteristics under different flow conditions are evaluated and the results are compared with existing theoretical models. The results show that heat transfer in two-phase flow exhibits a more complex behaviour compared to single-phase flow and this should be taken into account in design and applications. Heat transfer in two-phase and single-phase flows shows significant differences in different systems and applications. Single-phase flows are generally characterised by lower pressure drops, while two-phase flows offer higher heat transfer coefficients. Both types of flows require different strategies to optimise heat transfer performance in systems such as heat exchangers.

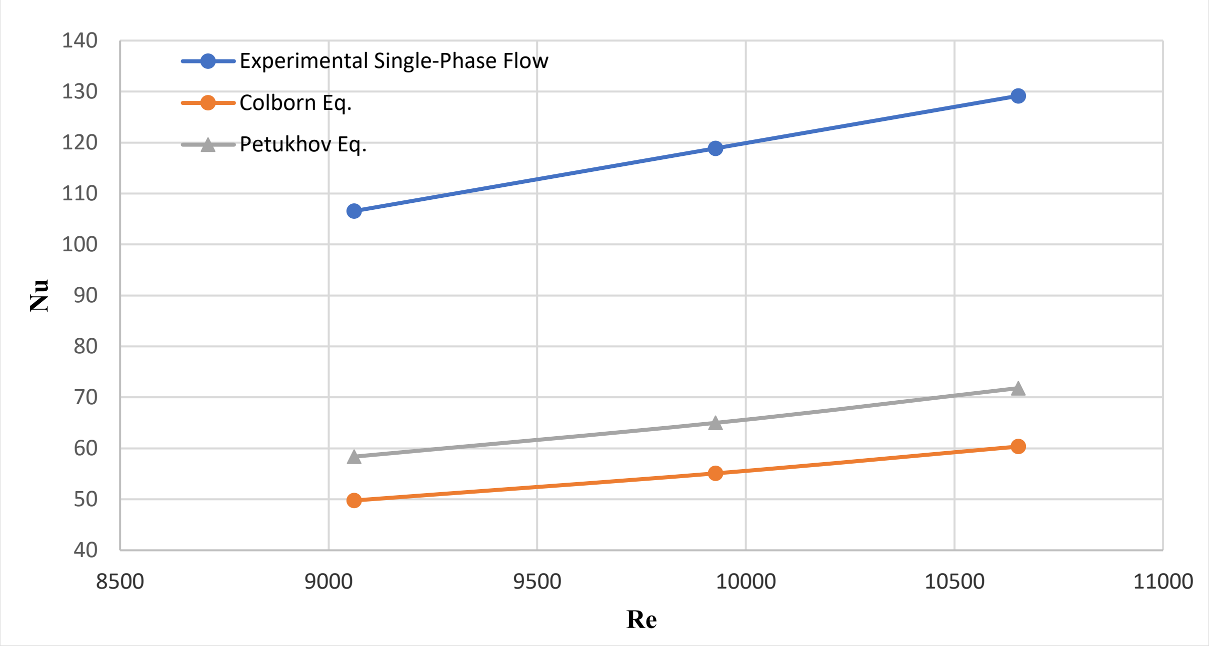

Figure 2. Nusselt-Reynolds number plot for pipe

Figure 2 shows the variation of Nusselt number with Reynolds number for the test section in its fully empty configuration. The experimental data were compared with well-established correlations by Colburn and Petukhov, which are applicable to turbulent single-phase flow in pipes [31-32-33]. The experimental Nu values, especially at higher Reynolds numbers, show strong agreement with these models, confirming that the data represent purely single-phase flow conditions. [34-35].

The best-fit correlation for the experimental data was obtained as: $Nu = 0{,}0487Re^{0{,}80}\,Pr^{1/3}$, which is consistent with classical turbulent pipe flow heat transfer behavior. However, under lower flow rates ($Re < 9000$), the thermal load on the system increases, and it has been observed that as flow rate decreases (Re decreases) in the 6000–9000 range, the flow begins transitioning into a two-phase regime. This transition cannot be identified directly from Figure 2, which includes only single-phase data. The onset of two-phase flow depends not on Reynolds number but on parameters like local surface temperature, heat flux, and fluid saturation conditions. Therefore, any analysis of the two-phase onset should be based on pressure drop behavior (Figure 3) or local wall temperature variations.

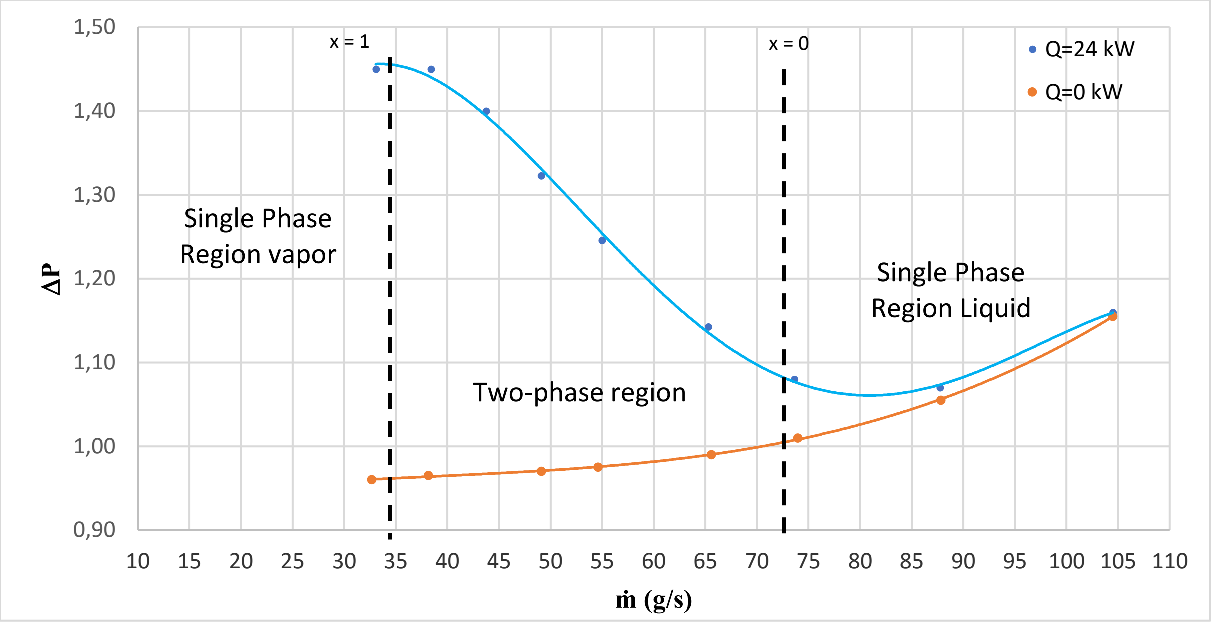

Figure 3. Steady-state characteristic curve for empty pipe in two-phase flow

When analysing two-phase flows, steady-state characteristics are shown by $\Delta p - \dot{m}$ graphs (Figure 3). Δp shows the pressure drop measured between the stabiliser tank and the point after the orifice plate at the end of the test pipe. The curve at the bottom of the figure shows the pressure drop for single-phase flow with no heat input to the system. Each of the curves for two-phase flow is in the shape of a slanted "S". The right sides of the curves corresponding to high mass flow values show the single-phase liquid region. As the mass flow rate decreases in the single-phase flow region, the pressure drop decreases and the slopes of the curves are positive in this region. With the decrease in flow rate values, the minimum point is reached where the single-phase flow regime ends. From this point, the two-phase region starts where the pressure drop decreases with the decrease in mass flow rate. In the two-phase region, the slopes of the curves are negative. This is due to the lower density of the vapour phase compared to the liquid phase, resulting in an increase in pressure drop and consequently an increase in the number of bubbles. When the flow rate is further reduced, all of the fluid in the pipe evaporates and after this point, a single-phase vapour region is formed where the pressure drop decreases [26-29].

Heat transfer and pressure drop in two-phase and single-phase flows are affected by many factors such as the type of fluid, pipe geometry and flow conditions. In two-phase flows, complex flow structures such as slug flow can significantly affect heat transfer and pressure drop. In single-phase flows, the pressure drop depends on simpler factors and can be optimised by proper pipe design. This information is important to increase energy efficiency and improve system performance [26-29].

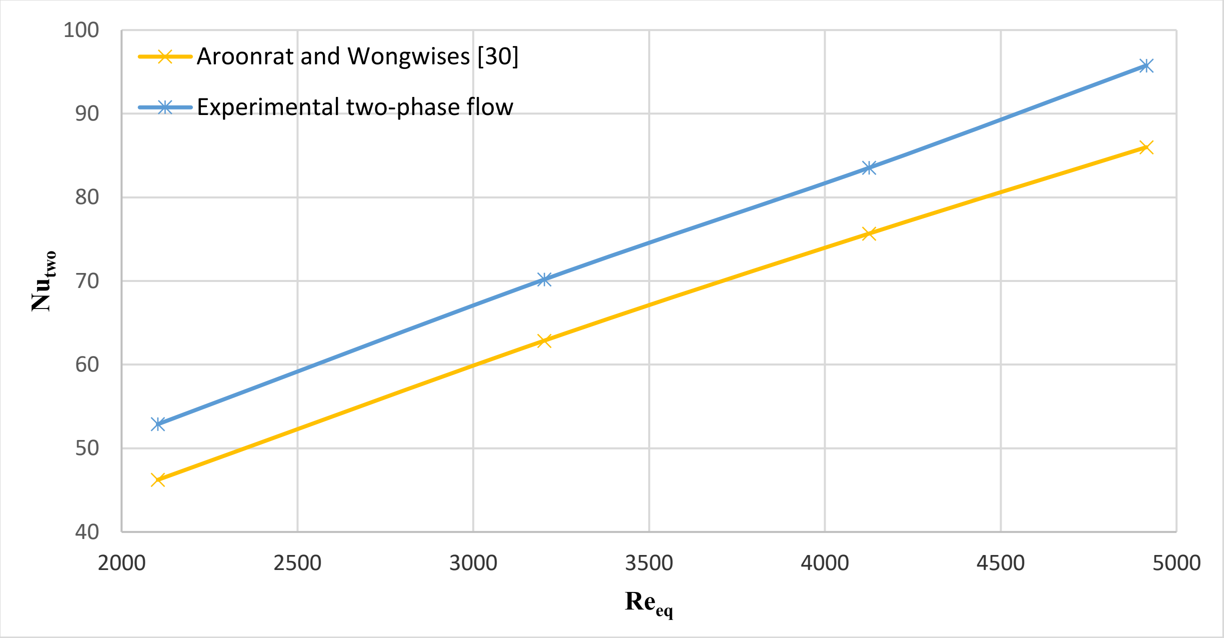

Figure 4. Nu- Re plot of two-phase flows in horizontal pipes

The graph in Figure 4 is drawn as the Nusselt number and equivalent Reynolds number. It shows that the Nusselt number increases with the increase of the equivalent Reynolds number. The reason for this is the heat transfer coefficient. Therefore, the Nusselt number increases as the equivalent Reynolds number increases. In addition, the slope of the Nusselt number is in agreement with the literature. Heat transfer in two-phase and single-phase flows shows significant differences in different systems and applications. Single-phase flows are generally characterised by lower pressure drops, while two-phase flows offer higher heat transfer coefficients. Both flow types require different strategies to optimise heat transfer performance in systems such as microchannel heat sinks [30]. In two-phase flow, heat transfer coefficients increase with increasing vapour quality and mass flow rate in microchannel heat sinks [6]. Moreover, in two-phase flow, the heat transfer properties of gas-liquid mixtures in different geometrical arrangements can be characterised by parameters such as Nusselt number and friction factor [7]. In single-phase flows, the heat transfer coefficients are primarily affected by the flow velocity and the hydraulic diameter of the channel. Higher velocities increase turbulence, which increases the Nusselt number and hence the heat transfer coefficient [3]. The presence of vapour bubbles increases heat transfer due to the latent heat of vaporisation and has higher heat transfer coefficients compared to single-phase flows [8].

Figure 4 illustrates the relationship between the Nusselt number and the equivalent Reynolds number for two-phase flow in horizontal pipes. As seen in the graph, the Nusselt number increases with increasing Re_{eq}, indicating enhanced convective heat transfer. This trend is primarily attributed to the rising heat transfer coefficient as the mixture velocity and vapor quality increase. The experimental results demonstrate higher Nusselt numbers compared to the correlation proposed by Aroonrat and Wongwises [30], although both exhibit similar slopes. The experimental Nusselt numbers consistently exceeded those predicted by Aroonrat and Wongwises (2017) across all measured Reynolds numbers. The results showed an average increase of 11.95% in the Experimental Nusselt number, indicating an improvement in heat transfer performance.

Heat transfer characteristics differ significantly between single-phase and two-phase flows. In general, single-phase flows are associated with lower pressure drops, while two-phase flows offer enhanced heat transfer due to phase change and interfacial phenomena. In two-phase flow through microchannel heat sinks, the heat transfer coefficient tends to increase with increasing mass flux and vapor quality [6]. Additionally, thermal performance in such flows depends strongly on geometric configuration, which influences both the Nusselt number and friction factor [7].

In contrast, in single-phase flows, the Nusselt number is mainly governed by flow velocity and channel hydraulic diameter. Higher velocities promote turbulence, thereby increasing both the Nusselt number and the heat transfer coefficient [3]. The presence of vapor bubbles in two-phase flow further enhances heat transfer through latent heat of vaporization [8].

Based on the measured flow rates, Reynolds numbers, and mass flow rates, the flow regimes in the experimental setup are classified as follows:

- $\dot{m}$>~73 kg/s → Single-Phase Liquid Region

  In this range, no boiling occurs and the working fluid remains entirely in the liquid phase. The Nusselt numbers align well with classical single-phase correlations like Colburn and Petukhov.

- $\dot{m}$≈34–73 kg/s → Two-Phase Flow Region

  This is the transitional range where local wall temperatures approach saturation and vapor bubbles begin to form. The negative slope observed in the Δp–V curve is a strong indicator of this regime. Sharp increases in heat transfer may occur due to latent heat effects.

- $\dot{m}$<34 kg/s → Single-Phase Vapor Region

  This range corresponds to full vaporization of the fluid. The pressure drop increases again, and heat transfer is solely due to vapor phase convection, which may be lower than in the two-phase region.

A similar classification can be made using mass flow rate ($\dot{m}$). High $\dot{m}$: liquid flow; low $\dot{m}$: vapor flow; mid-range values: two-phase transition.

4. Conclusion

In this study, the heat transfer and pressure drop characteristics in single-phase and two-phase flow regimes are evaluated in detail by experimental investigations in a horizontal test pipe. The obtained results are compared with Colburn and Petukhov correlations in the literature and the Nusselt number correlation in the single-phase region is obtained as $Nu=0.0487Re^{0.80}Pr^{1/3}$ for empty pipe conditions. The experimental data were found to be in agreement with the correlations presented in the literature [32-33]. As expected, it was confirmed that the Nusselt number also increases with the increase in Reynolds number and this result is in line with the trends reported in the literature [34-35].

In the study, it was found that two-phase flow starts at $\dot{m}$ between 34 and 73 kg/s, while single-phase flow regime dominates in the regions after 73 kg/s. At the transition to the two-phase region, a decrease in heat transfer is observed due to the low heat transfer coefficient of the vapour bubbles. However, the increase in slope in the two-phase region indicates that the heat transfer during boiling is higher than that of single-phase flow. This supports the studies in the literature indicating that the heat transfer coefficient increases with increasing vapour quality and mass flow rate in two-phase flows [6-7].

Pressure drop analyses revealed characteristic trends in two-phase flows and it was determined that the transition to the two-phase region is clearly seen with slope changes, especially in Δp-$\dot{m}$ graphs. In the two-phase region, an increase in the pressure drop due to the decrease in density and an increase in the number of bubbles were observed. These results show that complex flow structures encountered in two-phase flows, such as slug flow, have significant effects on heat transfer and pressure drop. In single-phase flows, the pressure drop can be explained by simpler dynamics and can be optimised by appropriate pipe design.

The findings show that two-phase and single-phase flows directly affect thermal system performance and energy efficiency. The results showed an average increase of 11.95% in the Experimental Nusselt number, indicating an improvement in heat transfer performance. While lower pressure drops are observed in single-phase flows, two-phase flows offer higher heat transfer coefficients, necessitating the development of different optimisation strategies, especially in the design of systems such as microchannel heat sinks [3-8-30]. Therefore, careful consideration of flow regime, pipe geometry and operating conditions in system designs is critical for increasing energy efficiency and improving system performance.

Ethics in Publishing

There are no ethical issues regarding the publication of this study

Author Contributions

O.Y, H.G, A.K and S.K contributed to the design of the study and collection of data, O.Y, H.G and A.K. contributed to the writing of the article, and O.Y., S.K and Ö.Ç. contributed to the evaluation of the results.

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