Chapter 1
Introduction

In the introductory chapter, the relevance and motivation for doing research in the field of pressure drop and dynamic instabilities in two-phase flow is presented. Furthermore, an overview of historic research and its state-of-the-art is summarized, analyzed with regard to relevant blind spots, and followed by a deduction of objectives, the present work is based on. The chapter closes with an outline and a list of publications and contributions, associated with this research work.

1.1 Motivation

The major part of electricity consumption worldwide is generated by means of thermal transformation processes. All conventional biomass, coal, nuclear, and almost all natural gas and oil power plants (those with a bottoming steam cycle) use a process in which water is vaporized to operate steam turbines that drive generators, converting the thermal energy into mechanical and eventually electrical energy. In fact, in 2017, more than ¾ of the electricity generation worldwide was based on heat from burning fuels or from nuclear fission [20]. Moreover, evaporation and condensation processes are relevant for thermal management, heat pumps, refrigeration and cryogenics, chemical processing systems, and the gas industry, amongst others. Hence, two-phase flow plays a major role in today's and future's electricity generation and is of importance for numerous further industrial applications. State-of-the-art steam generators are water-tube boilers. These boilers consist of evaporator tubes arranged inside a furnace. Water flows through these evaporator tubes, gradually heating up and evaporating while exposed to the heated tube walls. It is of importance to know the pressure drop of two-phase flow in these systems to design the circulation pump in forced circulation processes or to know the circulation rate in natural circulation processes. Furthermore, depending on the process layout and operating parameters, dynamic instabilities occur during evaporation that can cause thermal-hydraulic inefficiencies. Oscillating system pressure, mass flow, and temperature is undesirable, as these oscillations reduce the life span of involved system components through increased mechanical vibrations and thermal stresses. Furthermore, process control is disturbed and the risk of dryout increases.

1.2 State-of-the-art

Research in the field of two-phase flow started more than 100 years ago. The German engineer Lorentz conducted his analysis of two-phase flow hydrodynamics in 1909 [1]. However, considerable interest in the field of two-phase flow instabilities was created by Ledinegg's studies from 1938 [2]. For obvious reasons, extensive research in the field of two-phase flow was conducted in nuclear engineering. A large amount of publications exists. Several reviews give an overview about analytical, numerical, and experimental investigations, such as Boure, Bergles, and Tong (1972) [4] and recent publications from Kakac and Bon (2007) [5] and Nayak and Vijayan (2008) [6]. Especially with regard to experimental investigations, these reviews provide an accurate overview about research work that has been carried out.

There are several experimental studies that deal with two-phase flow phenomena. The majority of all studies use vertically oriented test sections. These studies can be further subdivided into studies that use forced circulation and studies that use natural circulation as external characteristic. Furthermore, the working fluid is either a refrigerant or water. Tao et al. (2013) [9] studied density wave oscillations by using water as working fluid and natural circulation as external characteristic with a vertical test section. The same applies for Jain et al. (2010) [12], Baars and Delgado (2006) [15], and Kim and Lee (2000) [19]. Kruijf et al. (2004) [16] used a test rig with Freon-12 as working fluid. The external characteristic and test rig layout were the same with natural circulation and a vertically oriented test section. Xiong et al. (2012) [10] conducted experiments with water as working fluid in a vertical test section exposed to forced circulation. Furthermore, they were operating above the critical point of water. Yun et al. (2010) [13] used a similar test rig layout with water operating between 9.8 and 31.0 bar. A helical upward sloping test section with water and forced circulation was analyzed by Guo et al. (2001) [18]. Liang et al. (2011) [11] studied density wave oscillations and pressure drop oscillations with Freon-22 as working fluid. Kakac and Cao (2009) [14] studied both, vertical and horizontal test sections with Freon-11 and forced circulation. Studies with horizontally oriented test sections are rare. Ruspini (2013) [7] built a test rig with horizontal test section and forced circulation. He studied pressure drop oscillations and density wave oscillations with the refrigerant R134a as working fluid. Comakli et al. (2002) [17] used Freon-11 instead.

Recent studies deal with further investigation of density wave and pressure drop oscillations. Dorao (2015) [68] studied the period of density wave oscillations in a uniformly heated horizontal test tube experimentally. Sørum and Dorao (2015) [69] studied the effect of density wave oscillations on the boiling heat transfer coefficient. Zhang et al. (2018a) [70] investigated the relationship between changing the heat flux and inlet subcooling degree on the features of density wave and pressure drop oscillations. Park et al. (2018a) [72] studied the interaction between pressure drop oscillations and superimposed density wave oscillations. Zhang et al. (2018b) [71] analyzed the effect of the heat load distribution and the wall thermal capacity on the stability of the flow boiling. Finally, Park et al. (2018b) [73] observed the influence of the existence of a compressible volume in the system on the amplitude of the superimposed density wave oscillations.

In the past century, efficiency of thermal-hydraulic systems increased significantly. This happened mainly due to better knowledge of the systems and its components and correspondingly due to better prediction of system behavior and performance. Today, numerical simulations in 1-d, 2-d, and 3-d are state-of-the-art. 1-d simulations are used especially for overall process calculation, whereas 3-d simulations are mainly used for components. A detailed overview of theoretical research conducted on two-phase flow instabilities is given by Kakac and Bon (2007) [5].

Several research studies exist that analyze dynamic instabilities in two-phase flow experimentally and numerically. However, there are no recent studies that use demineralized water as the working fluid exposed to forced and natural circulation in horizontal evaporator tubes at low pressure. In fact, these configurations are quite common and of great interest, e.g. for vertical heat recovery steam generators with horizontal evaporator pipes in combined power plants or for concentrated solar power systems with direct steam generation. Furthermore, the majority of numerical studies use the simplified homogeneous flow model approach or the drift flux flow model, whereas the heterogeneous flow model approach might imply considerably higher accuracy for two-phase flow. There are only a few publications that compare results of numerical simulations using the homogeneous flow model and to the author's best knowledge no publications so far that compare results of numerical simulations using the heterogeneous flow model with experimental data of two-phase flow pressure drop and dynamic instabilities to evaluate the model's accuracy.

1.3 Objectives

This research work can be subdivided into two parts. The aim of part one of this research work is to experimentally analyze pressure drop and dynamic instabilities in evaporation processes using demineralized water as the working fluid exposed to forced circulation in horizontally oriented heated pipes at low pressure. In fact, only one horizontal pipe is used, as instabilities are more pronounced in one-channel configuration than in multi-channel configuration [8]. The following approach is pursued to work on part one of this research work: First, a test rig is designed, constructed, commissioned, and operated to obtain experimental data. Second, a physical parameter study is conducted to investigate the influence of any physical parameter in isolation on pressure drop and dynamic instabilities of two-phase flow. The aim of part two of this research work is to validate the homogeneous and the heterogeneous flow model of the dynamic simulation software APROS (Advanced Process Simulation Software) from VTT (Technical Research Centre of Finland) using the experimental data. First, a simplified process model of the experimental test rig is created. Second, a numerical parameter study is conducted using both the homogeneous and the heterogeneous flow model to analyze different numerical parameter and their influence on steady-state and dynamic simulation results in comparison to the experimental data. Third, a physical parameter study is conducted using the homogeneous and the heterogeneous flow model and the results are again compared with the experimental data. Finally, all results are used to draw dimensionless thermal-hydraulic stability maps to predict stable and unstable regions for different operating parameter sets.

Originality of this research work at-a-glance:

- Horizontally oriented heated pipe with water as working fluid at low pressure.
- Flexible test rig that enables:
    - forced and natural circulation,
    - huge variety of external characteristics (different slopes in operating point, from horizontal up to vertical) to analyze their influence on the occurring oscillations (frequency and amplitude),
    - operating conditions to measure density wave and pressure drop oscillations.
- Numerical parameter study with homogeneous and heterogeneous flow model and comparison with experimental data.
- Dynamic simulation of pressure drop and dynamic instabilities with heterogeneous flow model and comparison with homogeneous flow model and experimental data.

In this research work, two interdependent two-phase flow topics are investigated in detail for different operating parameter sets both experimentally and numerically. First, the characteristic pressure drop versus mass flow curve, called “N-shape curve”, for steady-state operating conditions of adiabatic and diabatic pipe sections. Second, density wave oscillations’ stability boundaries and characteristics of the oscillation, such as frequency and amplitude. Hence, after this introductory Chapter 1 and after providing some background on two-phase flow (Chapter 2), the work is structured into four main parts. Chapter 3 deals with the two-phase flow test rig, its process design and main components. Chapter 4 deals with mathematical models of dynamic simulation (homogeneous and heterogeneous flow model), the numerical solution method, and introduces simplified process models to simulate two-phase flow pressure drop and density wave oscillations. Chapter 5 presents the experimental results and Chapter 6 the dynamic simulation results both for steady-state N-shape curves and density wave oscillations. The work closes with a conclusion and outlook Chapter 7.

1.4 Publications and contributions associated with this research work

Publications in international peer-reviewed journals:

- Temraz A, Alobaid F, **Lanz T**, Elweteedy A, Epple B. Operational Flexibility of Two-Phase Flow Test Rig for Investigating the Dynamic Instabilities in Tube Boiling Systems. In revision for: Frontiers in Energy Research. 2020
- Alobaid F, Al-Maliki W, **Lanz T**, Haaf M, Brachthaeuser A, Epple B, Zorbach I. Dynamic simulation of a municipal solid waste incinerator. Energy. Volume 149, 15 April 2018, Pages 230-249.
- Alobaid F, Mertens N, Starkloff R, **Lanz T**, Heinze C, Epple B. Progress in dynamic simulation of thermal power plants. Progress in Energy and Combustion Science. Volume 59, March 2017, Pages 79-162.
- Mertens N, Alobaid F, **Lanz T**, Epple B, Kim H-G. Dynamic simulation of a triple-pressure combined-cycle plant: Hot start-up and shutdown. Fuel. 2016;167:135-48.

Publications in peer-reviewed conference proceedings:

- **Lanz T**, Alobaid F, Epple B. Design and construction of a test rig to analyze thermal-hydraulic phenomena in two-phase flow. 24th International Conference on Nuclear Engineering (ICONE24), Charlotte NC, USA; June 2016.

Oral conference presentations:

- **Lanz T**, Alobaid F, Epple B. Design and construction of a test rig to analyze thermal-hydraulic phenomena in two-phase flow. 24th International Conference on Nuclear Engineering (ICONE24), Charlotte NC, USA; June 2016.

Supervision of Bachelor- and Master-theses:

- Co-supervisor Master Thesis: Müller L C. Dynamic simulation of flow instabilities in heated pipes. December 2017.
- Co-supervisor Bachelor Thesis: Peiler C. Printing of a scaled model of the 1 MW_{th} fluidized bed pilot plant with a self-constructed 3-d RepRap printer. September 2017.
- Co-supervisor Bachelor Thesis: Göksal M. Investigation of pressure drop in two-phase flow. December 2016.
- Co-supervisor Bachelor Thesis: Schon M. Construction and commissioning of a test rig to analyze thermal-hydraulic phenomena in two-phase flow. September 2016.
- Co-supervisor Master Thesis: Sanfeliu A. Dynamic simulation of a forced circulation and a once-through Heat Recovery Steam Generator system using PPSD. August 2016.

- Co-supervisor Bachelor Thesis: Neuberger N. Design of a test facility to analyze flow instabilities in boiling processes. November 2015.
- Co-supervisor Bachelor Thesis: Sanchez J. Design of a test facility to analyze flow instabilities in boiling processes. November 2015.

Chapter 2
Background

This chapter introduces basics of two-phase flow, such as flow regimes in vertical and horizontal heated pipes, heat transfer during evaporation, dimensionless numbers to compare thermal-hydraulically similar systems, and pressure drop in two-phase flow – the characteristic “N-shape curve”. Furthermore, the two-phase flow instability phenomena are introduced, and the mechanisms of the most common types are explained.

2.1 Two-phase flow basics

Two-phase flow is a particular example of multiphase flow. In contrast to single-phase flow, two states of matter exist in parallel. These two phases (solid-liquid, solid-gas, liquid-gas or liquid-liquid) are typically from the same substance (e.g., water and steam). However, flow with different substances per each phase (e.g., ash particles in flue gas) is also considered as two-phase flow. The most common two-phase flow in steam generators is liquid-gas (on the water/steam side) and solid-gas (on the flue gas side). The focus of this research work is the water/steam side, hence, liquid-gas two-phase flow.

Two-phase flow can be characterized by means of the following numbers:

- The **steam quality** (also called steam content) x of a flow is the quotient of the mass of the vapor phase m_v and the sum of the vapor mass m_v and the liquid mass m_l of the flow:

$$x = \frac{m_v}{m_v + m_l} = \frac{\rho_v A_v}{\rho_v A_v + \rho_l A_l} \tag{1}$$

- The **vapor volume fraction** α_v (also **void fraction**) is the quotient of the volumetric vapor fraction and the total volume of the flow, expressed by the cross-sectional area A_v of the vapor phase and the total flow cross section $A_v + A_l$:

$$\alpha_v = \frac{A_v}{A_v + A_l} \tag{2}$$

- The **slip ratio** S is a measure of the speed difference between the speed of the vapor phase $u_v$and the speed of the liquid phase u_l. In the homogeneous model, the slip ratio is assumed to be 1, i.e., the two phases flow at the same speed:

$$S = \frac{u_v}{u_l} \tag{3}$$

- **Relation between void fraction and steam quality**:

$$\alpha = \frac{1}{1 + \frac{\rho_v}{\rho_l} S \frac{(1-x)}{x}} \tag{4}$$

The ratio of steam quality x to void fraction α_v highly depends on the saturation pressure. The difference in density between the two phases decreases with increasing pressure. Figure 1 shows the steam quality versus void fraction for different pressures. At low saturation pressures, the curve is very concave and the void fraction approaches 1 for already small steam qualities. The curves continue to flatten out as the pressure increases. At the critical pressure $p_{crit} = 220.6\ bar$, both phases have the same density $\rho_v = \rho_l$ and the quotient in Equation 1 corresponds exactly to the quotient in Equation 2 and the following applies: $x = \alpha_v$. The curve assumes a linear course for this critical pressure.

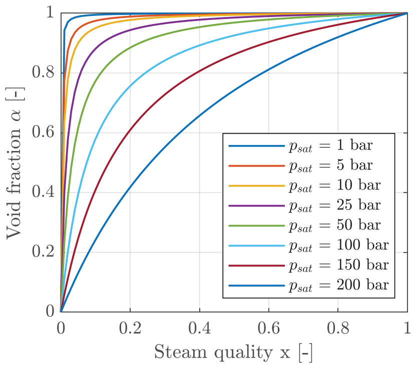

Figure 1: Relationship between steam quality and void fraction

When boiling in pipes of a steam generator occurs, several physical phenomena overlap and complicate the description of the process. In contrast to purely convective heat transfer, additional variables that play a role in phase change must be taken into account. Important variables are the enthalpy of vaporization, the boiling temperature, the density of the vapor and the interaction of the two phases, to name a few. Due to the increasing steam content in the direction of flow within the evaporator tubes, various boiling phenomena and flow regimes occur. [23]

2.1.1 Flow regimes

The water and steam phases can be distributed differently on the cross section of a channel or pipe in dependence on steam quality, superficial velocity (velocity as if there is no other phase available) of each phase, and flow-channel orientation (horizontal, vertical or inclined). These different distributions are known as flow regimes (also frequently called flow patterns). Important physical parameters that influence the flow regime are surface tension, fluid velocity, heat flow from the wall and gravity. In Figure 2 and Figure 3, the basic types of flow regimes in a horizontal and in a vertical heated tube (flow from bottom to top) are illustrated. In both tubes, the medium enters the inlet of the heated pipe as subcooled water and leaves the outlet of the heated pipe as superheated steam.

In the horizontal heated pipe (Figure 2), the following flow regimes may appear: single-phase water, bubbly flow, plug flow, slug flow, churn flow, annular flow, droplet flow, and single-phase steam flow. Furthermore, mixed and transition flow regimes can be observed.

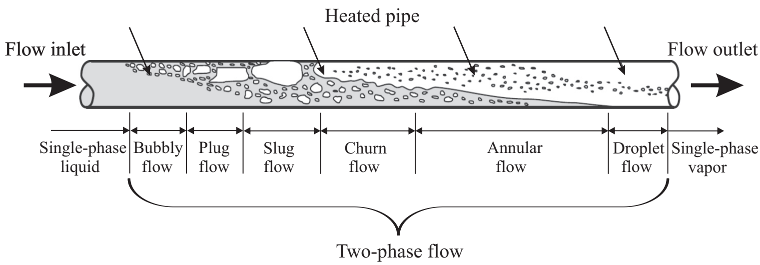

Figure 2: Two-phase flow regimes in horizontal heated pipes [26]

A bubbly flow occurs with a small gas volume flow. Due to the horizontal stratification and the associated influence of gravity, the bubbles move at the highest cross-sectional area in the mixture. With increasing gas volume and constant mass flow, the bubbles become larger and grow together into gas pistons. These generally move faster than the layers of liquid, which causes the gas pistons to push the layers of liquid. Due to the pressure difference, the gas pistons cannot continue to exist due to a further increase in the gas volume fraction. A stratified flow is created in which the gas and the liquid flow through the pipe in two layers one above the other. [52] As the velocity increases further, the interactions at the interface between the gas and the liquid phase become noticeable. The higher speed of the gas leads to a wavy surface of the liquid. With an ever increasing speed difference between the gas and the liquid, the waves create whole liquid gushes similar to a shock in a supersonic flow. This type of flow leads to high pressure losses, so that it must be given special consideration in the technical design of components. By further increasing the gas throughput and reducing the liquid content, the flow forces exceed the effects of gravity. An annular flow (film flow) occurs, in which the gas flows inside. The liquid is pressed against the wall and is in a circular cross-section between the gas and the pipe wall in order to minimize the energy dissipation in the system. When the speed of the gas becomes very high, the shear stress forces between the gas and the liquid exceed the adhesive forces of the liquid on the wall, so that a mist flow arises. The liquid is transported through the gas phase in the form of drops; there is then no longer any liquid on the inner wall of the pipe. [51]

In the vertical heated pipe (Figure 3), the following flow patterns may appear: single-phase water, bubbly flow, plug flow, slug flow, churn flow, annular flow, droplet flow, single-phase steam flow and again mixed and transition flow regimes.

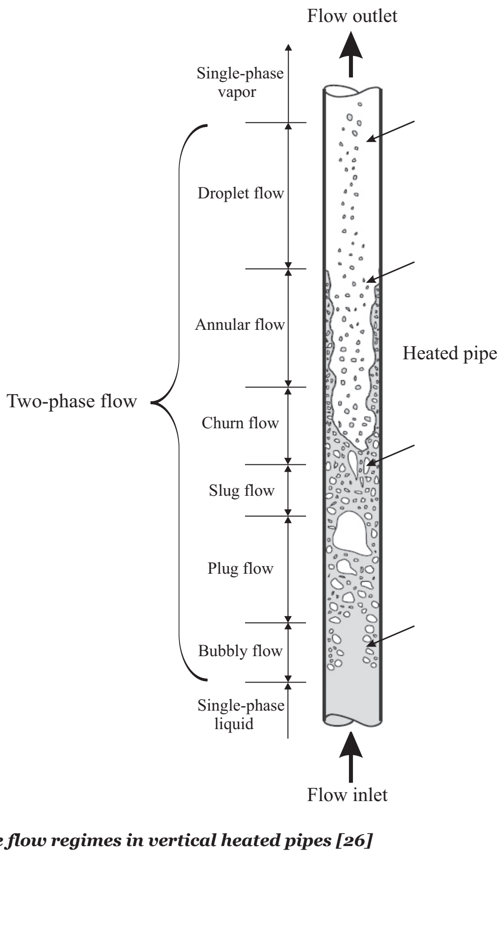

Figure 3: Two-phase flow regimes in vertical heated pipes [26]