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Experimental investigation of the dynamic thermohydraulic behaviour of vertical tube reboilers

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Abstract. The dynamic thermohydraulic behaviour of a vertical tube reboiler is investigated. Natural circulation reboilers are widely used in chemical industries, especially as column heater. Their main components are an evaporator and a separator which are connected in a loop. The product fluid coming from the separator is heated and partially evaporated. Entering the separator the two-phase flow is separated into liquid and vapour phase, due to gravity. As a result of evaporation the mean density of the fluid decreases. Caused by the density difference between evaporator and separator contents, a natural circulation occurs. Under certain conditions flow instabilities will occur, triggered by different causes. To investigate these instabilities and to distinguish between them as to their type a technical pilot plant scale test facility is used. Its main components are an evaporator, a separator and a condenser. The steam heated evaporator is designed as a straight tube heat exchanger with seven tubes of 4 m length each. By varying various operating parameters such as product vapour pressure, heat load and submergence level stable and unstable conditions can be observed and analysed. Based on the experimental results and criteria found in literature a stability diagram will be developed.

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1. Introduction

Natural circulation reboilers are widely used in chemical industries, especially in rectification processes. As another application thermosyphon reboilers are used for passive cooling in nuclear power plants. Their simple construction, the absence of moving parts and low operating costs are the main reasons for this. When used as a column heater the main components are an evaporator and a separator. Both are connected in a loop. Typically designed as a vertical tube heat exchanger the evaporator is normally heated by condensing steam. Coming from the separator the product liquid fluid is heated and partially evaporated in the evaporator, which results in a difference of the mean density between separator and evaporator. As a result, a self-induced, natural circulation occurs. Natural circulation systems are subject to several types of flow instabilities. The characterisation and classification of flow instabilities in natural circulation systems have been investigated in many studies, especially in the field of nuclear power technology, which are presented in the next section.

2. Principles of instability

Under certain conditions flow instabilities are present in natural circulation reboiler systems which cause undesirable flow oscillations. As a result difficulties occur while controlling and operating the reboiler systems. Also mechanical damages to the components caused by vibrations are reported. Due to these issues a stable operating status is of importance. Recent overviews of two-phase flow instabilities can be found in Nayak and Vijayan [1], Kakac and Bon [2] and Goswami and Paruya [3].

A flow is considered to be stable if, following a temporary disturbance, its new operating conditions show an asymptotically tendency to the initial behaviour. Instabilities can be classified according to various bases as follows [1]:

- analysis method,
- propagation method,
- number of unstable zones,
- nature of oscillations,
- loop geometry,
- disturbances or perturbations.

With respect to their mechanisms flow instabilities can be classified in two main groups, static and dynamic instabilities, which are both divided in various subgroups [4]. Static instabilities can be predicted by steady-state laws and can lead either to a different steady-state condition or to a periodic oscillating behaviour. The group of static instabilities includes for example flow excursion or Ledinegg instability, flow pattern transition instability, geysering and chugging. Dynamic instability is present when neither the cause nor the threshold of instability can be predicted from the steady-state laws as inertia and feedback effects have an important part. Dynamic instability can be divided in fundamental or pure dynamic instabilities such as acoustic oscillations and density wave oscillations and compound dynamic instabilities as thermal oscillations, BWR instability and parallel channel instability [4]. Density wave instabilities have been investigated experimentally and classified into two types, DWI I and DWI II, by Fukuda and Kobori [5]. Table 1 shows an overview of the various types of flow instabilities.
Table 1: Types of flow instabilities.

| Static instabilities                               | Dynamic instabilities                      |
|-----------------------------------------------------|---------------------------------------------|
| - Ledinegg instability                              | - Acoustic instability                      |
| - Boiling crisis                                    | - Density wave oscillations (I, II)         |
| - Geysering                                         | - Pressure drop oscillations                |
| - Instability due to change in flow regime          | - Thermal oscillations                      |
|                                                    | - Parallel tube instability                 |

One aim of this study is to develop a stability diagram as shown in figure 1, where the stable and unstable regions are divided by a stability boundary.

![Stability Diagram](image)

**Figure 1:** Typical stability diagram [4]

On the abscissa the heating or the dimensionless phase change number is plotted. On the ordinate you can find the subcooling at the inlet of the evaporator or the dimensionless subcooling number. Both dimensionless numbers are defined in [6]. The desired operating modus of a natural circulation reboiler is marked by region 2, where a steady circulation flow with completed boiling at the exit of the evaporator is present. Geysering, chugging and DWO type I can be assigned to region 1 as an unstable operating status. Region 3 is a second unstable region and mainly characterised by DWO type II. The above mentioned types of instabilities are affected by a variety of geometric and operating parameters which result in various different courses of the stability boundary curve and the characteristic of region 2. Important geometric parameters are the length and diameter of the evaporator tube and its surface quality. As described below the geometry will not be changed during the experiment. As important operating parameters pressure, inlet subcooling, heating power and submergence level are identified [5]. Kumar et al. have carried out various experiments investigating the stability boundaries at various pressures and inlet subcooling [7].

The following section describes the experimental setup used for this study and how the measurements are conducted.

### 3. Experimental description

The test facility built in a technical pilot plant scale stretching over two floors consists of three key parts: the evaporator, the separator and the condenser. All components including the connecting pipes are made of stainless steel. To minimise heat loss, all parts are insulated.
Fig. 2a and 2b show the test facility on two floors, ground floor and basement.

Fig. 3 shows the schematic of the test facility. The evaporator is designed as a vertical tube bundle with seven tubes of 4 m length each. Their outer diameter is 30 mm and the wall thickness is 2 mm.
Fig. 4 shows a cross section of the evaporator with the adapters for pressure sensors. Superheated steam provided by a natural gas fired boiler is lead into the shell side of the evaporator and condenses at the outer surface of the tubes. Via a pneumatic valve the steam pressure can be varied and controlled. The condensed water leaving the evaporator at the lower side is conducted back to the boiler. The studied product fluid (water) coming from the separator is heated and leaves the evaporator tubes in a two-phase status.

![Cross section of the evaporator with its adapters for pressure sensors](image)

**Figure 4:** Cross section of the evaporator with its adapters for pressure sensors

Entering the separator the two phases are separated due to gravity into liquid and gas phase. The vapour phase flows to the condenser passing a demister. The separator consists of a cylindrical vessel with a volume of 0.65 m$^3$ where the liquid phase of the product is collected.

The condenser is built as a straight tube heat exchanger with 110 tubes of 2.5 m length each. The outer diameter is 18 mm and the wall thickness is 1 mm which results in a total heat transfer area of 8.2 m$^2$. The vapour phase of the product coming from the separator is condensed and flows to the lower part of the separator. Ground water fed by a cooling pond is used as cooling fluid. As an important parameter the pressure on the product vapour side is varied by changing the amount of air inside the loop connecting either a vacuum pump or compressed air. It is additionally controlled by a pressure valve mounted on the condenser shell side.

During the experiment different temperatures, pressures and flow rates and the submergence level are measured. For measuring the flow rate of the overheated steam entering the evaporator and the product vapour leaving the separator ultrasonic flow meters, Panametrics GS 868, apply. The metering point of product vapour flow rate named FM3 is shown in fig.3. Their uncertainty increases at low flow velocity up to +10 %. To obtain proper data as well as comparable values of the flow rate of superheated steam, a turbine flow meter is mounted in the condensate pipe with an uncertainty of 1 %. The flow rate of the circulating product at the lower side of the evaporator and the returning subcooled liquid product from the condenser are measured by ultrasonic flow meters, Panametrics UPT 868 P. The metering points named FM1 and FM2 are shown in fig. 3. They have calibrated using an oval wheel counter. Their uncertainty has been determined to be up to 7 %. As this method is contactless no additional pressure drop is introduced. The flow rate of the cooling water is measured by a turbine flow meter with an uncertainty of less than 1.2 %.

The wall temperature of each evaporator tube is measured at two levels, 1 and 2 m below the top face of the evaporator, by 14 thermocouples, Type K, soldered at the outer surface of the tubes. At the inlet and outlet of the evaporator the temperature and pressure of the product fluid is measured by thermocouples and absolute pressure sensors. Inlet temperature and pressure of the overheated steam are measured by a thermocouple and an absolute pressure sensor. Its condensate temperature is measured by a thermocouple at its outlet of the evaporator. The thermocouples have an accuracy of 0.1 K. Additionally platinum resistance thermometers PT100 are used for measuring the temperatures
of the product vapour leaving the separator and its condensate entering the separator, same for the inlet
and outlet temperatures of the cooling water of the condenser and the inlet temperature of product
fluid of the evaporator. The platinum resistance thermometers have an accuracy of 0.02 K.

The pressure drop across each of the seven evaporator tubes is measured by difference pressure
sensors. A bypass level indicator, Kobold NBK-03, is used to measure and display the submergence
level in the separator.

All measurement outputs are sampled by a NATIONAL INSTRUMENTS® data acquisition
system NI cDAQ-9188®. The PC software LabVIEW® is used for editing, visualizing and saving the
values in a text file for further evaluation. A continuous sampling at various sampling rates ensures the
exposure of the dynamic behaviour of the test loop.

3.1 Experimental procedure

To indicate their influence on the thermohydraulic behaviour of natural circulation reboilers
various operating parameters have been investigated. The pressure on product vapour side at the outlet
of the evaporator can be varied in a range between 0.4 and 2.0 bar (abs), which corresponds to
saturation temperatures between 75.86 °C and 120.21 °C. To investigate the influence of the driving
temperature difference and the heating power the superheated steam can be conditioned in a pressure
range between 3 bar and 7 bar, at a temperature range between 140 °C and 190°C. Its mass flow rate is
determined by the heat demand of the evaporation in the evaporator tubes. As a further parameter the
submergence level as a driving force can be varied between 60 % and 110 % of the evaporator height.

To achieve reasonable results especially in terms of heat transfer energy balances of all components
are used which are calculated and plotted online by LabVIEW®. The uncertainty of heat transfer
calculated with measured values is approximately 10 %.

4. Results

First experiments have been conducted for testing the system and measurement components.
Preliminary results have been generated which are presented here. During these experimental runs
only stationary operating states have been investigated. Different pressures on product and heating
steam side have been investigated, in which the temperature of heating steam held constant.

Table 2: Test matrix with investigated pressure conditions

| Pressure on product side in bar | Pressure on heating steam side in bar |
|-------------------------------|--------------------------------------|
| 1.0                           | 4, 4.5, 5, 5.5, 6                    |
| 1.5                           | 4, 4.5, 5, 5.5, 6                    |
| 2.0                           | 4, 4.5, 5, 5.5, 6                    |

Table 2 shows the test matrix. The various combinations of pressures result in various temperature
differences between heating steam and product fluid. Fig. 5 shows preliminary results where the
subcooling at evaporator inlet over heat flow is presented at a submergence level of 100 %. It can be
observed that, while holding all other parameters constant with increasing product pressure the
subcooling decreases. As the temperature difference between heating steam and product increases with
a higher pressure of heating steam, the heat flow increases.
The subcooling also shows a slightly increase with growing heating steam pressure. At these conditions no oscillations have been observed. Hence these parameter configurations can be assigned to region 2 in fig. 1.

As shown in fig. 6, where the circulating mass flow rate in kg/s is presented over the time in seconds, an increasing pressure on the product side results in increasing circulating mass flow at constant heating steam conditions as temperature and pressure. A reason for this could be that caused by the higher temperature difference a higher heat transfer coefficient is present, which results in a higher steam quality and two-phase pressure drop due to friction and hence a decrease in circulating mass flow rate. The observed oscillations are in a range of max. +/- 25 % in case of $p_{\text{product}} = 2$ bar. As an indication of instability some authors report amplitudes of 30 % of the mean value.
Fig. 7 shows the steam quality (●) and mass flow rate (+) presented over heat flow. It can be observed that, as mentioned before, with increasing heat flow the steam quality $x$ increases and the mass flow decreases.

**Figure 7**: Steam quality $x$ at evaporator outlet and mass flow rate over heat flow at stationary conditions.

5. Conclusion

To investigate the stability of natural circulation reboilers a technical pilot plant scale test facility has been built. First experimental runs have been conducted to evaluate the measurement system. In the course of these experiments only stationary conditions have been investigated. Preliminary results of these tests are presented.

In upcoming experiments the dynamic behaviour of natural circulation reboilers will be investigated to find criteria for indication of stability. On base of these tests a stability diagram can be developed as shown in fig.1. Furthermore tests under instationary conditions will be conducted in detail to explore the principles of flow instabilities, the nature of oscillations and their propagation. In an additional step a simulation model will be developed to evaluate the experimental results.

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