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School of Science  
Department of Applied Physics

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## **Exercise D: Heat Transfer and Boiling Phenomena**

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(eds.)

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**Summary:**

This report contains instructions for a laboratory exercise that demonstrates heat transfer and different boiling modes. This is done with Hilton Boiling Heat Transfer Unit H653.

The original instructions were in Finnish. They were translated to English in 2015.

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# 1 Heat Transfer in Pool Boiling

Boiling is a common process in our everyday life. Most typical examples include heating up water on a stove for a cup of tea and heat exchange in a fridge or a freezer.

In energy technology, the boiling heat transfer is an essential and important process. The main reason is that the evaporation and condensation of liquids are more effective in terms of heat transfer than cooling or heating without a phase change. In many applications, boiling often requires high pressures and temperatures and includes risk of drying, which is why the boiling has been previously avoided. Because of the research and experiments on boiling processes, they are understood better today and can be controlled more accurately. Some examples of the current applications of boiling heat transfer are boiling water reactors, different types of heat exchangers and centralised solar collectors.

Boiling is either pool boiling or flow boiling. In pool boiling the liquid-vapour mixture fluid is restricted into a certain volume and in flow boiling the fluid is flowing in a condenser tube, for example.

In pool boiling a heat source is in a fluid container, whose volume is significantly larger than the volume of the heat source. There is no driven convection, and currents in the fluid are significant only in the vicinity of the heat source [1]. A common everyday example of pool boiling is boiling water in the kettle. In energy technology pool reactor is a typical example.

In spite of the greater number of practical applications of flow boiling, pool boiling has been studied more comprehensively, because pool boiling experiments are easier to implement. Pool boiling results are applicable to flow boiling as well, when the currents are small, which is the case in most heat exchangers.

## 1.1 Boiling Modes

One-phase heat transfer depends mainly on the temperature difference between the surface of the heat source and the liquid; absolute temperatures affect only the flow properties of the liquid. In boiling (two-phase heat transfer) the absolute temperatures as well the temperature differences become relevant for heat transfer, so a convenient choice for the reference temperature is the saturation (evaporation) temperature of the liquid in the given pressure. Therefore, we can define the overheating of heat source surface  $\Delta T_{sat} = T_w - T_{sat}$ , where  $T_w$  is the surface temperature of the heat source, and  $T_{sat}$  the saturation temperature of the liquid. As well we can define the subcooling of the liquid  $\Delta T_{sub} = T_{sat} - T_l$ , where  $T_l$  is the temperature of the liquid.

The condition  $\Delta T_{sat} > 0$  must be satisfied for heat transfer from the heat source to the liquid. In this sense, boiling can be defined to be one type of heat transfer, where the liquid is in the saturation temperature and  $\Delta T_{sat} > 0$ . Thus, the heat flux from the surface is then used to evaporate the liquid. The nature of boiling changes drastically when  $\Delta T_{sat}$  or the heat flux increases.

## Convection Boiling

There are no bubbles in boiling, when  $\Delta T_{sat}$  and the heat flux are small. This type of boiling is called convection boiling; the liquid in the vicinity of the heat source expands and causes convection currents in the liquid. Expanded and less dense liquid rises to the surfaces where it evaporates. Heat transfer in this mode is relatively weak due to a small amount of convection. In colloquial language, convection boiling is not usually considered as boiling, where the criteria is the bubble formation instead of steam production.

## Nucleate Boiling

To understand mechanisms of bubble formation, we start from the homogenous bubble formation theory. In order to hold a bubble together, a pressure inside the bubble must be higher than the surface tension induced pressure of a liquid on a vapour-liquid interface:  $p_g > p_l(\sigma)$ . Since  $p_g$  is the vapour pressure corresponding the temperature of the liquid  $T_l$ , the condition

$$T_l(p_g) = T_g(p_g) > T_{sat} \quad (1)$$

must be satisfied.

The smaller the bubble is, the higher the pressure  $p_g$  inside it is. Thus, a larger temperature difference is needed on the interface in order to hold the bubble together. There is an analogy to birthday balloons: when a balloon is small, blowing more air into the balloon is hard, since the pressure inside the balloon is higher. But when the volume of the balloon increases the pressure decreases and the blowing becomes easier. Therefore, forming an infinitely small bubble would require an infinite temperature difference.

Naturally, this classical "balloon model" does not apply on the molecular level, but explains the bubble growth after the birth of the bubble. Explanation of the bubble birth requires quantum mechanics and it is not considered here. The quantum mechanical homogenous bubble formation theory gives only a few bubbles per cubic centimetre when  $T_{sat} = 10$  K, so the mechanism of bubble formation cannot be purely homogenous, meaning that the bubble formation depends on location.

Let us take a look into the heterogenous bubble formation theory. The contact angle is defined as an angle  $\xi$  between the liquid and the solid surface as illustrated in Fig. 1. The contact angle depends on the surface tension of the liquid, the roughness and the purity of the surface to mention. Since the contact angle has always a value greater than zero, the surface never wets completely, but instead the gas pocket are formed into the sharp edged pits on the surface as illustrated in Fig. 2. These gas pockets act as nucleation sites for the bubble formation. When the liquid is heated up to the saturation temperature, it evaporates into the nucleation site from the interface and the bubble starts to grow. The balloon model explains the bubble formation fairly well from this point on.

When the bubble is sufficiently large, the pressure inside the bubble (as well the density) is small enough for the buoyancy to uplift the bubble from the heat

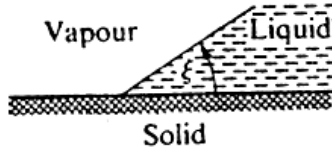


Figure 1: The contact angle between the liquid and the surface [1, p. 129].

source surface and transport it to the liquid-vapour interface on top of the liquid. In the case of the sub cooled liquid, the vapour condensates into the liquid, but if the liquid is in the saturation temperature, vapour is released on the top surface of the liquid.

The liquid flowing into the place of an uplifted bubble causes turbulence in the liquid, which enhances the heat transfer significantly compared to convection boiling. Bubble formation happens all the time in the activated gas pockets and when the heat flux increases, the number of activated gas pockets increases.

Nucleation boiling bears strong turbulence and therefore has a high heat transfer coefficient. In nucleation boiling,  $\Delta T_{sat}$  is never really high, because of the high heat transfer coefficient. So, nucleation boiling is clearly the most important boiling mode for the applications.

## Film Boiling

When the heat flux is increased further, the successive bubbles start forming vapour slugs which transport vapour to the top surface of the liquid. Eventually, the vapour slugs merge and a vapour film on the heat source surface is formed. This is illustrated in Fig. 3. Across this vapour film, heat can transfer only by conduction or radiation. Since the heat transfer coefficient decreases drastically,  $\Delta T_{sat}$  increases rapidly which might lead to the melting of the heat source, so called burnout. In boiling water reactors, the consequence can be the melting of the fuel rods and severe nuclear accident.

However, film boiling is stable when  $\Delta T_{sat}$  is high enough; the conduction and radiation, both depending on  $\Delta T_{sat}$ , can transfer all the produced heat into the

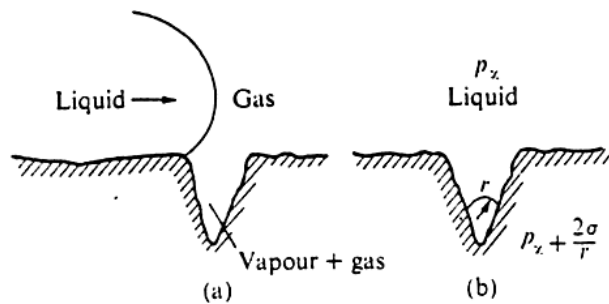


Figure 2: Gas pockets on the surface of the heat source [1, p. 145].

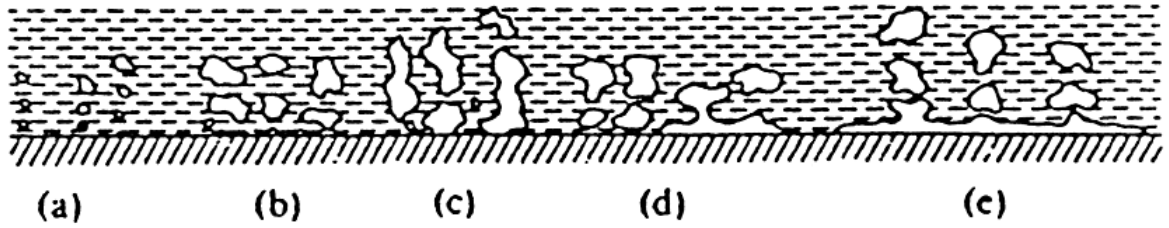


Figure 3: Boiling modes: (a) separate bubbles; (b),(c) vapour slugs; (d) film boiling transition; (e) film boiling [1, p. 131].

liquid. Bubbles are uplifted from the surface of the vapour film and raise normally to the top surface of the liquid. Roughness of the heat source surface is not relevant in film boiling in contrast to nucleation boiling. Film boiling around a horizontal cylinder shaped heat source is shown in Fig. 4.

There are many risks in film boiling and that is why it is usually avoided in the applications. However, the stable film boiling can be studied using some cryogenic liquids, which have  $T_{sat}$  low enough.

## 1.2 Interpretation of Boiling Curves

The results of pool boiling experiments are usually represented as boiling curves. In a boiling curve, the heat flux between the liquid and the heat source is plotted as a function of  $\Delta T_{sat}$ , usually using a logarithmic scale. In measurements, either the heat flux or the temperature of the heat source can be controlled, so different variations of the curves exist.

### Heat flux As a Control Parameter

Let us assume that the heat flux is gradually increased (by electric heating *e.g.*) from zero to the certain maximum and then gradually decreased back to zero. This type of boiling curve is shown in Fig. 5(a).

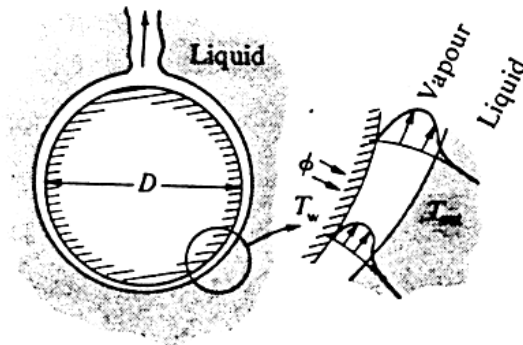


Figure 4: Film boiling around a horizontal cylinder shaped heat source [1, p. 139].



When the heat flux is small, the main mechanism of heat transfer is convection boiling up to point A, heat transfer is weak, and even the slightest change in the flux increases the temperature difference significantly. When the bubble formation begins at point A, the heat transfer coefficient increases rapidly, and the temperature difference decreases even while the heat flux increases (from A to B). This phenomenon is called *boiling curve hysteresis*. It depends on the liquid-surface combination and does not occur in all types of systems. When there is no boiling curve hysteresis, the boiling curve goes from J to B directly.

Between points B and C the nucleation boiling occurs and heat transfer is efficient; an increase in the heat flux causes only a minor increase in the temperature difference. Eventually, with the increasing flux, the bubble formation increases until point C, after which a minor increase in flux can increase the temperature difference greatly.

From point D onwards, a vapour film starts forming as described earlier, and between points D and E, the temperature difference increases rapidly when the vapour film covers the surface of the heat source. Point D is called the *departure from nucleate boiling* (DNB) and the corresponding heat flux is called the *critical heat flux* (CHF). In literature, the process between the points D and E is called *the first boiling crisis, heat transfer crisis or burnout*.

Stable film boiling begins from point E, if the equipment has not melted yet. Now the conduction and the radiation across the vapour film is sufficient to transfer all the produced heat, and increase in the heat flux up to point F does not anymore increase  $\Delta T_{sat}$  infinitely. When the film is once formed, it stays stable even when the heat flux is decreased below the CHF, so the boiling curve goes from point F to point G. In point G the film starts to break down and the heat transfer enhances rapidly and the temperature difference decreases until point H where the system returns into nucleation boiling. Point G is called *Leidenfrost-point* and the corresponding heat flux is the minimum heat flux for film boiling. The region between points G and H is called *the second boiling crisis*. When the flux is decreased further, the boiling curve returns smoothly from nucleation boiling to convection boiling following path H-B-J.

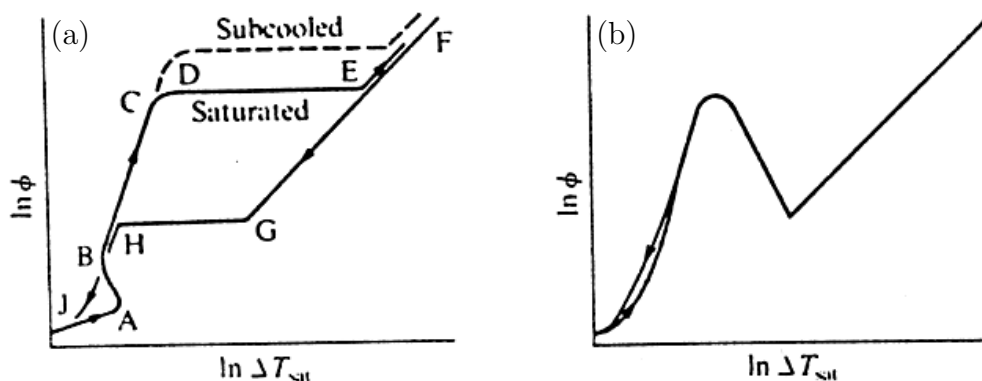


Figure 5: A boiling curve with the (a) heat flux, (b)  $T_w$ , as a control parameter [1, p. 130].

## Surface Temperature of the Heat Source As a Control Parameter

When the surface temperature of the heat source is used as a control parameter instead of heat flux, there is no hysteresis phenomenon. Then the boiling curve is the same in both directions and transition boiling (partial film boiling) connecting the points D and G appears. This type of boiling curve is shown in Fig. 5(b). In this regime boiling fluctuates constantly between nucleation boiling and film boiling: the surface is fully covered, by turns, both vapour film and liquid. With a proper experimental setup, the surface temperature of the heat source can be kept constant, so transition boiling becomes fully stable.

### 1.3 Factors Affecting Boiling

#### Structure of the Surface and Liquid

The number of the activated gas pockets depends on the quality of the heat source surface. Consequently, the number of activated gas pockets affect the starting point of nucleation boiling, the steepness of the boiling curve in nucleation boiling, and the temperature difference in the DNB-point. This dependency has been studied by processing the surface of the heat source in order to form artificial pits, holes and cavities on the surface [1–3]. Activation of the gas pockets depends also on the contact angle which depends on the surface tension of the liquid and the chosen liquid-surface combination. Therefore, for each different surface and surface-liquid combination, the beginning of the boiling curve differs (see Fig. 6). However, the named factors do not affect the critical heat flux, Leidenfrost-point or film boiling. Even if there are plenty of experimental results and some empirical, correlation-based, formulas available [2,3], there is no single unifying quantitative theory which combines all of the factors above and explains the shape of the boiling curve.

#### Geometry

The geometry of the system does not significantly affect the nucleation boiling as long as the dimensions of the heat source surface are larger than the size of the formed bubbles. Nevertheless, geometry affects how easily bubbles can escape from the surface (compare bottom of the plate and thin wire *e.g.*), and thus, geometry affects the CHF and film boiling.

#### Pressure

Overheating of the heat source surface  $\Delta T_{sat}$  decreases as the internal pressure of the container increases, and CHF reaches its maximum value when  $p \approx 0.3p_{crit}$ , where  $p_{crit}$  is the thermodynamical critical pressure of the liquid (see Fig. 7). In the regime of small pressure ( $p < 0.1p_{crit}$ ) the dependency is nearly linear.

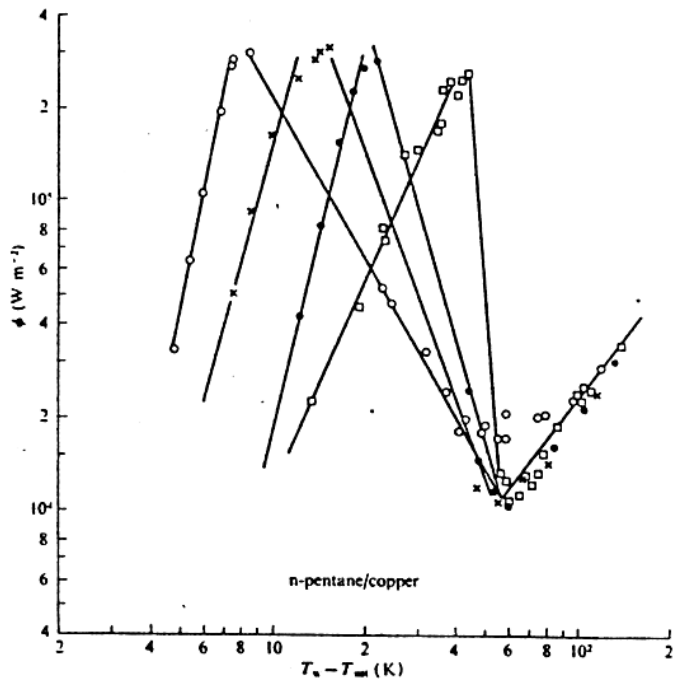


Figure 6: Boiling curves for different surfaces [1, p. 133]. Symbols:  
 ○ = lap; × = emery 60; ● = emery 320; □ = mirror finish.

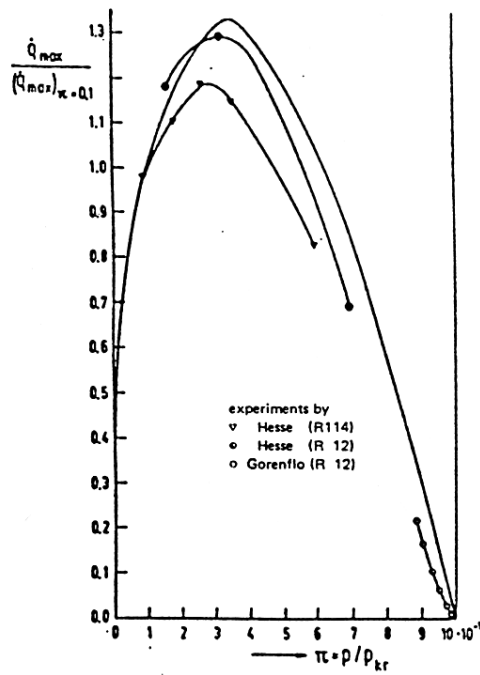


Figure 7: Effect of pressure on the critical heat flux [2].

## 1.4 Quantitative Examination of Boiling

Heat transfer in boiling is one of the last "black holes" in the experimental physics; despite the large amount of experimental data and results, the one single unifying quantitative theory, explaining the relations between the essential factors of the boiling, is lacking. So far only empirical and semi-empirical formulas based on dimension analysis between certain quantities have been presented. Nucleation boiling has turned out to be especially tricky to model. In the following we will restrict ourselves to the mathematical description of the computation of CHF.

Kutateladze [4] used dimension analysis and experimental data in 1952 to derive a semi-empirical formula for CHF, when the surface of the heat source is a horizontal wire or narrow plate:

$$\phi_{crit} = 0.13h_{lg}\sqrt{\rho_g} \sqrt[4]{\sigma g (\rho_l - \rho_g)} . \quad (2)$$

In 1958, Zuber confirmed the formula: just below CHF, nucleation boiling exhibits counter-current flow, in which the *vapour currents from* the heat source surface and the *liquid currents to* the heat source surface are in equilibrium (see Fig. 8). Critical condition for this typical "traffic problem" can be obtained from the Helmholtz stability condition

$$\frac{\sigma 2\pi}{\lambda (\rho_l + \rho_g)} > \frac{\rho_l \rho_g}{(\rho_l + \rho_g)^2} (V_g - V_l)^2 , \quad (3)$$

where

$$\lambda = 2\pi \sqrt{\frac{\sigma}{g (\rho_l - \rho_g)}} \quad (4)$$

is the oscillation wavelength of the interface.

In equilibrium, mass currents cancel out and we can write a mass balance equation for the system:

$$V_g \rho_g = V_l \rho_l . \quad (5)$$

Combining Eqs. (3) and (5) leads to stability condition

$$\frac{\rho_l \sigma 2\pi}{\lambda \rho_g (\rho_l + \rho_g)} > V_g^2 , \quad (6)$$

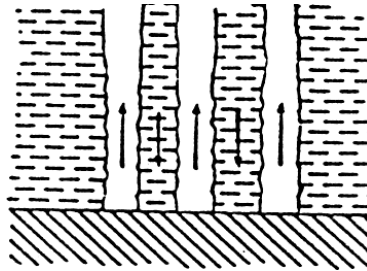


Figure 8: Stable counter-current flow [5].

where the maximal velocity of the escaping vapour is

$$V_g = \sqrt{\frac{\rho_l \sigma 2\pi}{\lambda \rho_g (\rho_l + \rho_g)}}. \quad (7)$$

By substituting  $\lambda$  in Eq. (4) into the Eq. (7), the stable maximum velocity can be written as

$$V_g = \sqrt[4]{\frac{\sigma (\rho_l - \rho_g) g}{\rho_g^2}} \sqrt{\frac{\rho_l}{\rho_l + \rho_g}}. \quad (8)$$

The heat flux of the escaping vapour can be obtained by multiplying the velocity of the vapour current of Eq. (8) by the heat (enthalpy) of vaporisation  $h_{lg}$ , the vapour density  $\rho_g$ , and the constant  $C$  describing the surface coverage area of vapour slugs in the stability limit. Thus,

$$\phi_{crit} = C h_{lg} \rho_g \sqrt[4]{\frac{\sigma (\rho_l - \rho_g) g}{\rho_g^2}} \sqrt{\frac{\rho_l}{\rho_l + \rho_g}}. \quad (9)$$

When  $\rho_l \gg \rho_g$ , Eq. (2) by Kutateladze can be recovered from Eq. (9)

Zuber experimentally determined the value 0.13 for the constant  $C$  agreeing with the previous result by Kutateladze. Later on, Rohsenov suggested constant  $C$  to be 0.18 [1].

## 2 Experimental Setup

Experimental setup in this exercise consist of Hilton Boiling Heat Transfer Unit H653 [6]. Diagram of the unit is shown in Fig. 9.

An electrical heating element (heat source) is placed in a cylindrical horizontal copper cover which is embedded into a vertical cylindrical glass container, approximately 5 cm below the liquid level. Thus the criteria for pool boiling is met. The surface temperature of the heating element is monitored using a thermocouple and a digital thermometer. Absolute accuracy of the thermometer is poor, so before any measurements, the values of the digital thermometer should be compared with an analogical one to obtain the systematic error of the thermometer. The experimental setup includes a controller which shuts down the electric current through the heating element if the temperature exceeds 170 °C. Voltage over the heating element is controlled with a transformer of the range 0–160 V with corresponding heating power 0–800 W.

A condenser coil is placed above the liquid level in top of the glass container. Cooling water circulates in a nickel coated copper coil. Vapour, produced by the heating, condensates on the surface of this coil and drops down. The current of cooling water can be controlled in the range 0–50 g/s. By changing the current, the amount of condensing vapour and therefore the pressure in the container can

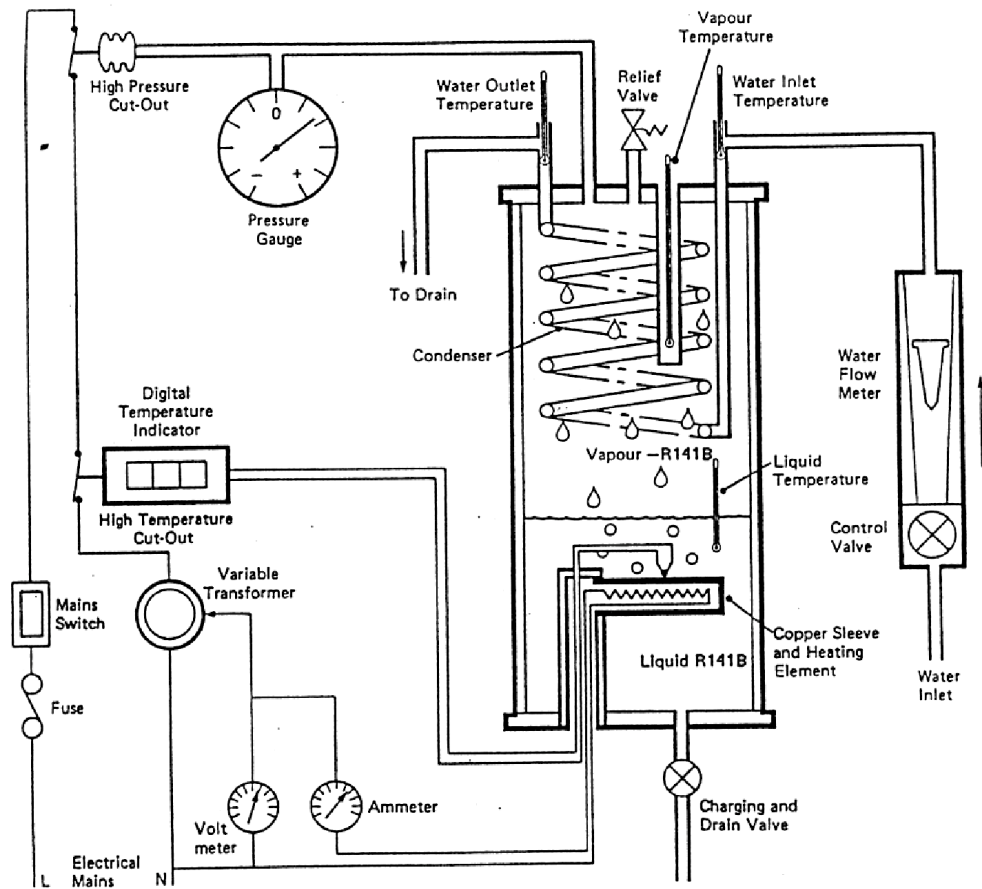


Figure 9: Experimental setup [6].

be adjusted. The pressure gauge is wired to the controller which shuts down the electric current through the heating element if the pressure exceeds 230 kPa.

Additionally, the setup includes four glass thermometers which measure the temperatures of the liquid and vapour in the container and inlet and outlet temperatures of the cooling liquid in the range 0–50 °C. The boiling liquid is 1,1-Dichloro-1-fluoroethane, R141B, which has a suitable saturation temperature and pressure properties for this experiment. The setup can be used for the following purposes for example:

- demonstration of different boiling modes,
- measurement of the heat flux and the heat transfer coefficient,
- measurement of the critical heat flux as a function of pressure,
- heat transfer into the cooling liquid by film condensation.

## 3 Laboratory Exercise

### 3.1 Heat Flux and Heat Transfer Coefficient in Constant Pressure

In measurements, the values of voltage and the pressure might vary every year, so the following values are not necessary accurate. The assistant will give the correct values for voltage and pressure during the exercise.

1. Set the voltage over the heating element to 20 V and keep the cooling current at zero until excess pressure reaches the value 50 kPa. Keep the pressure in this value as accurately as possible by adjusting the cooling current continuously.
2. Wait approximately one minute until the thermometers have stabilised, and write down the values of voltage, current, liquid temperature and surface temperature of the heating element.
3. Increase the voltage over the heating element up to value 25 V and repeat the step above. Remember to monitor the pressure!
4. Repeat the measurement using the values of voltage given in measurement record to obtain the boiling curve around the critical flux.
5. Monitor the system carefully. In the beginning of film boiling, the heating power and cooling current must be rapidly decreased to almost zero to keep the system stable.
6. If you have managed to reach stable film boiling and the excess pressure value is 50 kPa, set the voltage to 70 V and record more data points to the boiling curve using the voltage in the range 70–90 V, so that the surface temperature of the heating element is in the range 140–170 °C.
7. Finally, decrease the power to zero and increase the cooling current to maximum value until the boiling in the container has ceased and the pressure is around atmospheric pressure.

### 3.2 Critical Heat Flux as a Function of Pressure

Repeat the procedure above until the DNB point is reached with the values of absolute pressure 175, 200 and 250 kPa. Write down the values of voltage and current of the heating element at the DNB point. Note the effect of pressure on saturation temperature and temperature difference at the DNB point. End the measurement by decreasing the power to zero value and pressure to atmospheric pressure.

### 3.3 Heat Transfer into the Cooling Liquid

Condensing vapour covers the cooling coil by forming continuous film of liquid on it. This is called film condensation, apart from the dropwise condensation, where the whole surface of cooling unit is not wetted [6]. Condensing vapour produces heat increasing the temperature of the cooling liquid and the heating power of condensation can be obtained as:

$$\dot{Q} = \dot{m}c_{pw} (T_o - T_i) . \quad (10)$$

1. Set the power, pressure and cooling current to the values low enough that boiling is nucleation boiling. Write down the voltage, electric current, cooling current and incoming and outgoing temperatures of the cooling water.
2. Repeat the measurement with constant power for different cooling currents and pressures.

### 3.4 Report

1. Describe briefly the performed measurements (outlines of the theory, experimental setup and the description of the measurement).
2. How the heat flux into the liquid is calculated? Justify.
3. Define the heat flux and heat transfer coefficient in the constant pressure (150 kPa of absolute pressure).
4. Plot the boiling curve and determine the critical heat flux (150 kPa of absolute pressure)
5. How does the heat transfer coefficient depend on overheating of the surface (150 kPa of absolute pressure)?
6. Based on the measurements, how does the critical heat flux depend on the pressure (150 kPa, 175 kPa, 200 kPa and 250 kPa of absolute pressure)?
7. Determine the parameter  $C$  in the formulas of Kutateladze and Zuber for the current experimental setup with its error limits. Use Eq. (2). Compare the value with the values reported by Kutateladze and Zuber. What is the origin of the possible difference?
8. Calculate the heating power of the condensing vapour in the different measurements and compare it to heating power. What is the origin of the possible difference?



## 4 Notation

$C$	constant
$c$	specific heat
$g$	gravitational constant (9,81 m/s <sup>2</sup> )
$h$	latent heat (enthalpy)
$m$	mass
$\dot{m}$	mass current
$p$	pressure
$Q$	heat
$\dot{Q}$	heating power
$T$	temperature
$\Delta T$	temperature difference
$V$	velocity
$\lambda$	wave length
$\xi$	contact angle
$\rho$	density
$\sigma$	surface tension
$\phi$	heat flux

### Indices

$crit$	critical
$g$	vapour
$i$	incoming cooling liquid
$l$	liquid
$lg$	transition from liquid to vapour
$o$	outcoming cooling liquid
$p$	constant pressure
$sat$	saturation
$sub$	subcooling
$w$	heating surface, water

## 5 Numerical Values and Units

- surface area of the heating element:  $0.0018 \text{ m}^2$
- surface area of the coiling unit:  $0.032 \text{ m}^2$
- volume of the glass container:  $0.0015 \text{ m}^3$
- voltage range of the heating element:  $0\text{--}160 \text{ V}$
- current range of the heating element:  $0\text{--}3 \text{ A}$
- pressure range inside the container:  $-100\text{--}250 \text{ kPa}$
- outside pressure (atmosphere):  $100 \text{ kPa}$
- specific heat of water  $c_{pw}$ :  $4.18 \text{ kJ/kgK}$
- heat flux:  $[\phi] = \text{W/m}^2$
- heat transfer coefficient:  $[H] = \text{W/m}^2\text{K}$

The assistant will hand out an info sheet of R141B with diagrams during the exercise.

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