

Flow Boiling Processes in the Thermosyphon Reboilers

I. Experimental set-up and the identification of boiling patterns

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In the thermosyphon reboilers the most processes for vapours generation are made by flow boiling, that is the movement of liquid on heat transfer surface by external forces. For this it is necessary a distinct meaning between the internal circulation of liquid produced by movement vapours bubbles and the global movement in system(column and reboiler). In order to identify these regimes an experimental set-up is made.

Key words:thermosyphon reboiler;flow boilings;boiling regimes

It is possible to divide the heterogenous boiling as function of total movement of liquid on heat transfer surface. There are two categories of boiling:

- a - pool boiling;
- b - flow boiling (an old term for this type is convective boiling).

For the first situation the liquid in boiling state has a movement on heat transfer area by natural convection induced by departure of bubbles from nucleation sites and their movement inside pool liquid (for exemple, the boiling water in batch vessel). In case b) over the pool boiling a forced movement of the liquid is superimposed by pumping liquid, a very good exemple is the boiling of the flowing fluids into tubes. The old term in saxon languages is "convective boiling", but the term "flow boiling" is usually used. This division is necessary for two types of boiling because the mechanism of bubble formation is function of liquid flow over thermal surface, in the first case the movement having natural pattern, while the other is forced flow.

Thus it is necessary an explanation about the boiling in thermosyphon reboilers for fractionating columns or desorbition towers. The liquid circulation inside system (reboiler and bottom of column) has a natural cause, but the flow on heat transfer surface in reboiler is forced flow because of different static pressures for bottom column and reboiler and, in this case column and reboiler are two different equipment, the bottom of column plays a role of gas-liquid decanter, moreover the liquid circulation having an imposed way. If the liquid is pumped at the same flow rate in reboiler the boiling in the reboiler tubes has the same pattern, while to introduce a mixing device inside a pool boiling vessel although natural convection is determined (established) by hydrostatic pressure the heat transfer is changed.

The classification and graphical presentations of flow boiling regimes in tubes, for upward flow is presented in many papers and books [1-3]. For horizontal flow boiling in tubes an eloquent graphical presentations is given by [1] and [4]. The flow boiling in vertical tubes has the following boiling regimes: convective heat transfer to liquid, partial subcooled boiling, full subcooled boiling, saturated nucleate boiling, forced convective heat transfer through liquid film (annular boiling) and liquid deficient regime (mist boiling). Over these boiling regimes, the vapours/liquid two-phase flow is superimposed.

Experimental part

The experimental set-up is presented in figure (1) having the following main parts: loop for boiling fluid, apparatus and the part for measuring liquid flow rate. The boiler is a vertical glass tube having $d_1=18$ mm, internal diameter, and $L=2000$ mm length. There is also plastic protection tube (2) with thermal and electrical insulation which upheld the boiler tube by three adjustable supports. The protection tube (2) is cut up over lateral edge having 2 cm width, 2m length as a window for view observations of boiling tube. On the rear part of the protection tube there are 11 bulbs of 4.5 V to light up the boiler tube. Thermal insulation of boiler tube is made by electrical sheet connected to low electrical transformer (4) which is of use for the lighting system and electrical insulation. Maximum voltage of the electrical sheets is 48V and at the time of measurement the load is fixed to 4-5 V to compensate the heat loss, but the boiling of liquid will be heated only by heating element.

The heating of liquid in boiler tube (1) is made with electrical resistance of carbon steel wire (5) having $d=1$ mm diameter being nonexpensive and allowing the measurements. In the old arrangement, the wire is placed on the center line of glass tube but is difficult to obtain the most two boiling regimes so that the power on volume of tube to be very little. A new heating element of spiral shape placed on the wall of glass tube is provided.

For the measurement of fluid temperature inside reboiler is provided a thermistor (resistance thermo-meter) which has the possibility of movement, upward and downward in the tube. A system of pulley device with expansion vessel (7) and seal drum (8) ensure sealing boiler tube figure (2). Electrical resistance of thermistor is measured after calibration with a digital multimeter (IPB). The pressure at the bottom of reboiler tube is measured by Bourdon gauge while a simple manometer is connected to expansion vessel for measurements of top pressure. The tube connection from boiler to downcomer is tight with Teflon tube and special putty.

The condenser (9) is placed above the downcomer having a cylindrical shell for separation liquid and vapours. Inside a bayonet heat exchanger with finned surface is cooled by tap water and measured by rotameter (11). The temperature of water is measured by a thermometer to inlet and to exit with a thermistor.

The recycle branch (downcomer) (12) is a glass tube having $d=30$ mm diameter and length $L=2000$ mm and it

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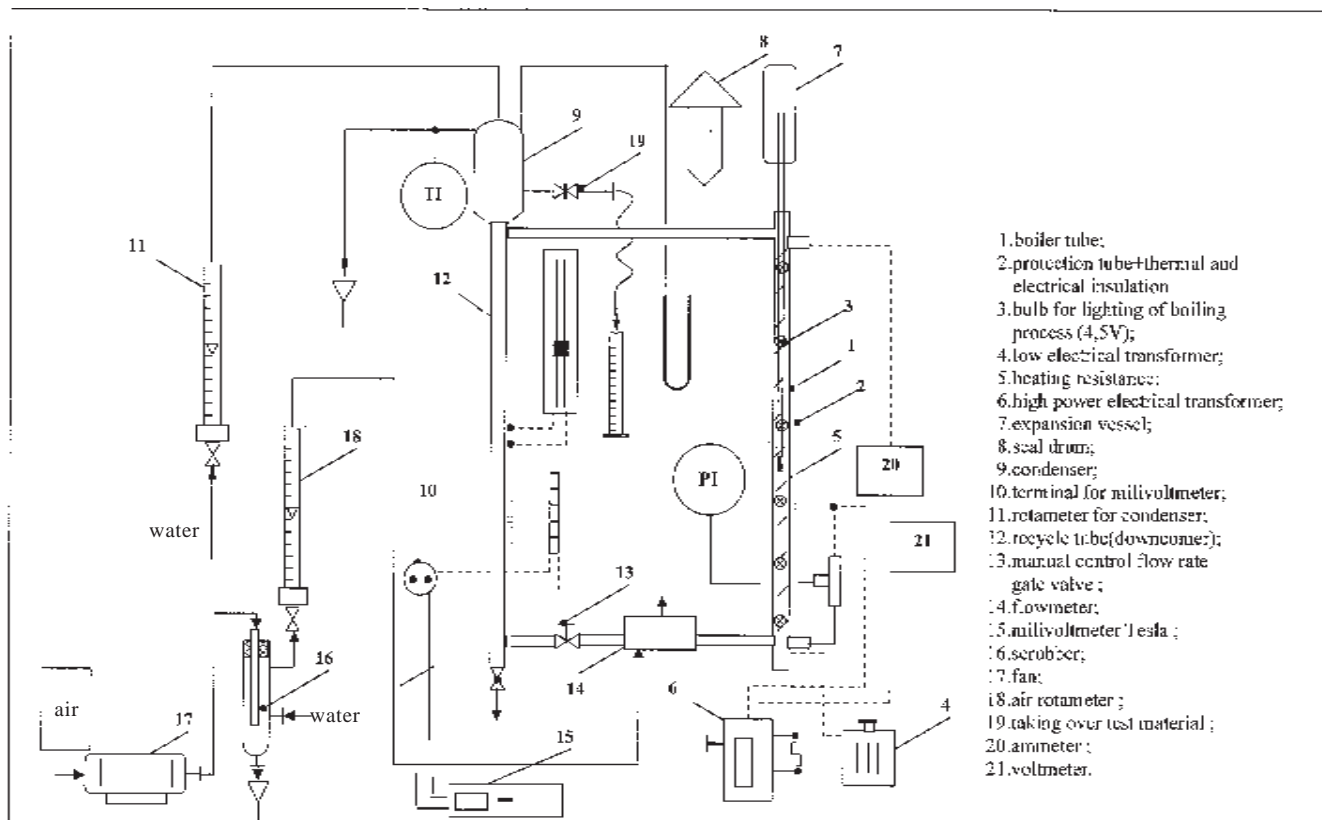


Fig. 1. Therosyphon reboiler set-up

- 1.boiler tube;
- 2.protection tube+thermal and electrical insulation
- 3.bulb for lighting of boiling process (4,5V);
- 4.low electrical transformer;
- 5.heating resistance;
- 6.high power electrical transformer;
- 7.expansion vessel;
- 8.seal drum;
- 9.condenser;
- 10.terminal for millivoltmeter;
- 11.rotameter for condenser;
- 12.recycle tube(downcomer);
- 13.manual control flow rate gate valve;
- 14.flowmeter;
- 15.milivoltmeter Tesla;
- 16.scrubber;
- 17.fan;
- 18.air rotameter;
- 19.taking over test material;
- 20.ammeter;
- 21.voltmeter.

is provided with protection tube, thermal and electrical insulation. The electrical insulation is connected to low voltage transformer and the accurate electrical load is made by a potentiometer. The drain of liquid is made by a ball valve to bottom downcomer. On the branch of downcomer with reboiler there is a gate valve (13) and a particularly flowmeter (14) is provided. The measurement of temperature differences of the air for flowmeter and temperature differences of liquid is made using two differential thermocouples and a Tesla millivoltmeter (15). The air for flowmeter is provided by a fan (17) after washing and cooling into scrubber (16) for constant exit temperature and his flow rate is measured by rotameter (18).

The measurement with special flowmeter of liquid flow rate is necessary owing to variation of feed liquid temperature to enter of reboiler, so that an assembly orifice plate and manometer will cause a great pressure drop and the diminution of circulation rate of reboiler. The flowmeter is represented by a little heat exchanger having an internal tube of copper with diameter $d=8$ mm and length $L=8$ cm and a glass shell. The flow rate to inlet of reboiler is obtained from heat balance

$$G_a c_{p,a} \Delta T_a = G \cdot c_p \Delta T \quad (1)$$

where:

- G_a –air mass flow rate, kg/s;
- G –fluid mass flow rate, kg/s;
- $c_{p,a}$ –air specific heat, J/Kg/K;
- c_p –fluid specific heat, J/kg/K;
- ΔT_a –air difference temperature, °C;
- ΔT –fluid temperature drop (maximum 1-2°C).

The next advantages of this apparatus are: simple shape, very little pressure drop, the possibility to fit the measurement range, the possibility to be using to gas-liquid mixtures. The principal problem is represented by the composition of fluid to establish the specific heat c_p .

The other possibility a circulation rate measure, in special conditions, is heat balance on the reboiler in form:

$$Q = L_p \cdot (t_e - t_i) + V \cdot [c_p \cdot (t_e - t_i) + r_v] \quad (2)$$

where:

- Q –heat transfer rate, W;
- L, V –liquid and vapours mass flow rate to exit of reboiler, kg/s;
- c_p –liquid specific heat, J/kg/K;
- r_v –latent heat, J/kg;
- t_i, t_e –inlet liquid temperature and vapours-liquid mixture outlet temperature of reboiler, °C.

$$G = L + V \quad (3)$$

It is possible to write eq. (2) eliminating the sensible heat transferred to fluid [5]:

$$Q = L \cdot c_p \cdot (t_e - t_i) + V \cdot r_v \quad (4)$$

and the load of condenser is equal with the heat of vapours. The form of equation (2) is then

$$Q = L \cdot c_p \cdot (t_e - t_i) + Q_c \quad (5)$$

or

$$L = \frac{Q - Q_c}{c_p \cdot (t_e - t_i)} \quad (6)$$

It will be noted that these equations are possible only in certain conditions such as: the place of heat source inside of liquid or perfect adiabatic system existence; accurately measurement of inlet and outlet temperature so that this difference is little for single component (1-2 degrees); in the situation when the liquid is subcooled, the circulation is modified very much; the measurement of bulk temperature over flow area; accuracy of heat transfer rate within condenser.

In the case of flowmeter (14) for liquid reboiler two

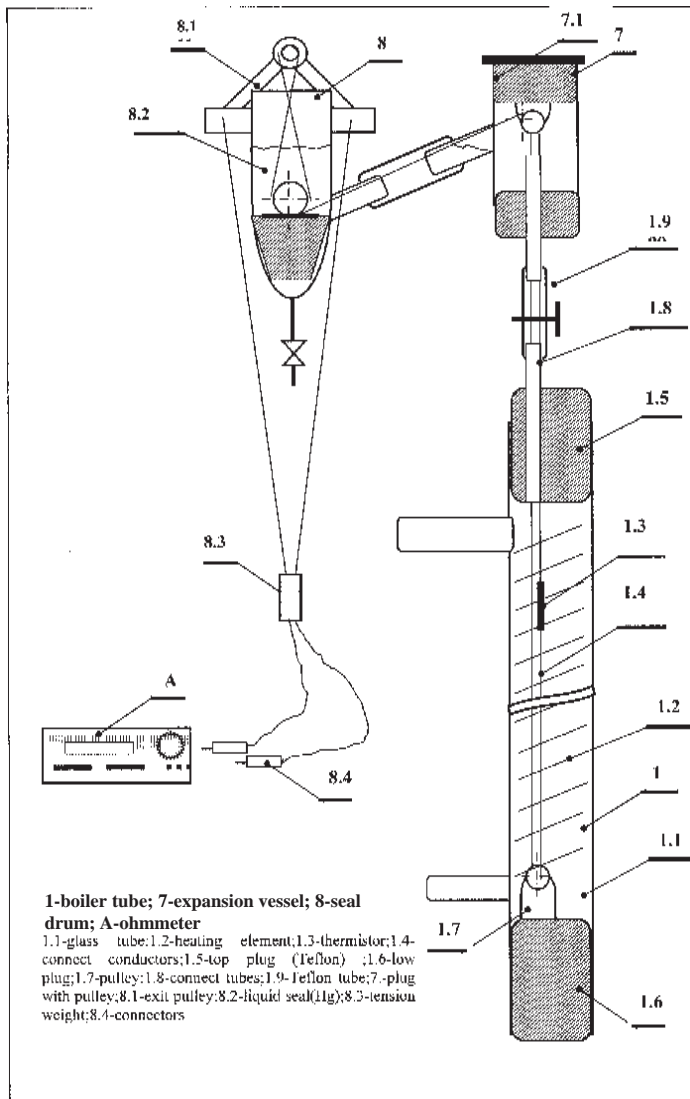


Fig. 2. Details of boiler tube

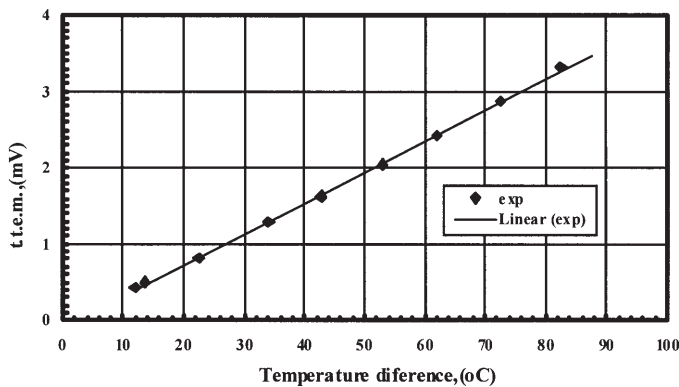


Fig. 3. The variation thermo-emf(t.t.e.m) for flowmeter (14); thermocouple of liquid

T (°C)	17,5	29,4	31	40	51,5	60,2	70,5	79,5	90	100
ΔT	0	11,9	13,5	22,5	34	42,7	53	62	72,5	82,5
ΔU_L	0	0,42	0,5	0,83	1,29	1,63	2,05	2,42	2,87	3,32
ΔU_{air}	0	0,43	0,5	0,84	1,3	1,64	2,08	2,44	2,88	3,3
$\Delta U/\Delta T$.034	.034	.05	.0367	.04	.04	.0408	.041	.0428	.045

Table 1
 THE VALUES OF THERMO-EMF OF THE FLOWMETER(14) THERMOCOUPLE

thermocouples have been calibrated one for liquid, the other for air, the data as described in table 1. while experimental points are plotted in figure (3) for liquid thermocouple and figure (4) for air thermocouple. The cold(reference)-junction temperature inside Dewar pot has been 17.5°C and because of the variations DU/DT are not constant regression points were made by linear and

parabola. The following equation is obtained:

$$\Delta U_L = 0.040662 \Delta T - 0.066456 \quad (7)$$

for thermocouple (copper-constantan) of figure 1.a) and

$$\Delta U_{air} = 0.040568 \Delta T - 0.066456 \quad (8)$$

for thermocouple(copper-constantan) of figure (2). The parabolic equation

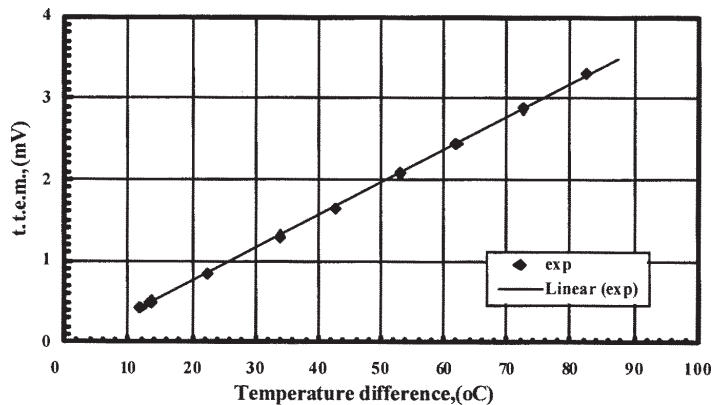


Fig. 4. Variation of thermo-emf (t.t.e.m.) for flowmeter (14); thermocouple for air

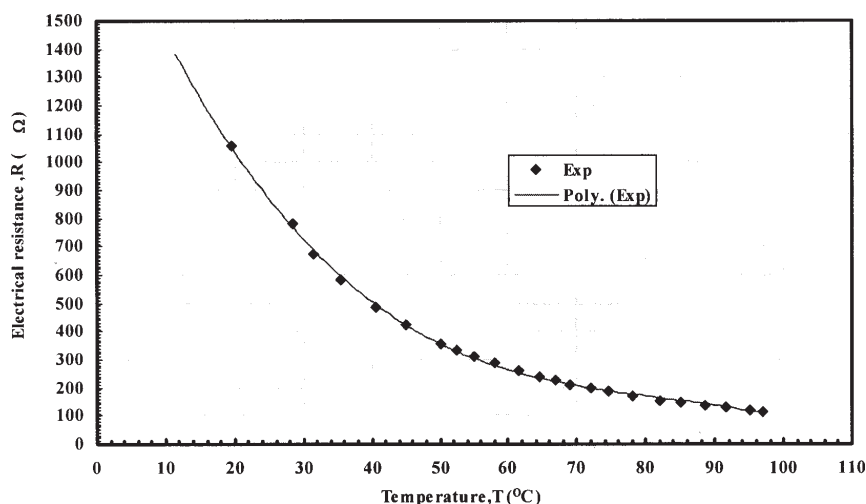


Fig. 5. Variation of electrical resistance of thermistor 2 versus temperature for boiling liquid within reboiler

$$\Delta U_L = -0.00482 + 0.03377T + 5.44474 \cdot 10^{-5} T^2 \quad (9)$$

$$\Delta U_{air} = -0.001385 + 0.03467T + 4.59839 \cdot 10^{-5} T^2 \quad (10)$$

The thermistors are used for the measurement of fluid temperature within reboiler and their calibration have been made with thermo-bath. The electrical resistance is measured by digital multimeter (IPB). In figure (5) experimental point is plotted for thermistor 2. In the first case correlation equation for thermistor is

$$R = 1997.92 - 70.08T + 1.083T^2 - 0.00807T^3 + 2.3504 \cdot 10^{-5} T^4 \quad (11)$$

comparatively with usually relationship for thermistors

$$R = 0.02844 \exp\left(\frac{3046.38}{T}\right) \quad (12)$$

Equation (12) is obtained by our experiment but using expression equation is reverse,

$$T = 256.96953 - 22.36 R^{1/2} + 0.79017 R - 0.01019 R^{3/2} \quad (13)$$

and for the data of figure (3).

$$T = 224.1471 - 15.831 R^{1/2} + 0.79017 R - 0.0101 R^{3/2} \quad (14)$$

The heating element is a carbon steel wire having spiral shape with 1 mm diameter, this type of heating is made when the cooling Newton law for used to heat transfer coefficients determination. The placement of a sensors on/in heat transfer area give distortions of temperature field of heat body or thermal boundary layer and, such heating system eliminates this problem.

The calibration of wire heating element is made with thermo-bath and voltmeter plus ammeter for the first case having electrical resistance

$$R_s = 0.1973 + 2.0634 \cdot 10^{-3} T ; [R_s] \equiv \Omega / m \quad (15)$$

For the second calibration has been made with thermo-bath and a Wheatstone bridge with direct current source of 9 V and as galvanometer is an ammeter IPB (the scale is mA with reference value of +0.2 mA). We have obtained an electrical resistivity

$$\rho_{el} = 0.1168 [1 + 5.546 \cdot 10^{-3} (T - 20)] ; [T] \equiv ^\circ C ; [\rho_{el}] \equiv \Omega \text{ mm}^2 / m \quad (16)$$

The shape of heating body is possible to be a wire such as used by Nukiyama for his boiling curve (1934), according to [6], metal film on support as silver on stainless steel [7] and ITO film on glass tube, [8] or metal tubes connected to high current electric transformers (in many papers) inside of tube having fluid boiling.

In figure (6) there are two set resistance experimental points for the second wire (heating element) and average values according to Kafarov method [9] with regression line having electrical resistivity defined by equation (16).

Results and discussions

A physical example of flow boiling in vertical tube is given by [10] for a flow in annular space and [11] and [22] for flow visualization of movement of steam/water inside riser, the mixture is obtained in [11] within four tube heat exchanger at the bottom of the riser. For the two-phase flow, a map for boundary flow regions of other authors together with their data is presented by [11]. A similar flow map for steam-water is the diagram of Hewitt and Roberts (1969) from [12].

In the horizontal flow boiling the principal regimes [1] are: bubbly, plug, slug, stratified (wavy), annular and mist flow. There is a difference between horizontal flow boiling inside conventional tubes and microchannels. Many

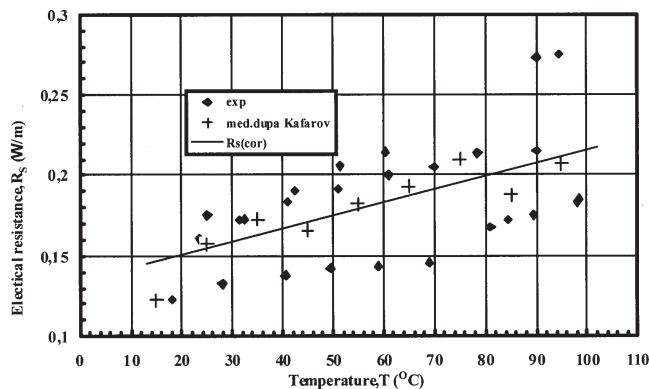


Fig. 6. The resistance of heating element versus temperature (second wire)

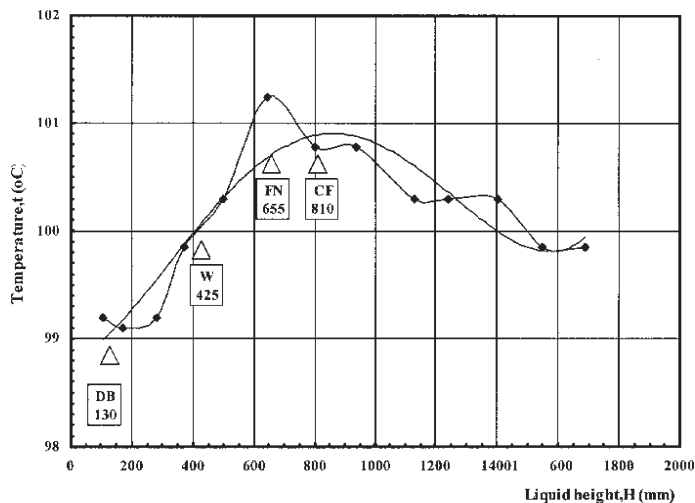


Fig. 8. Temperature profile at $q = 14884 \text{ W/m}^2$ (water)

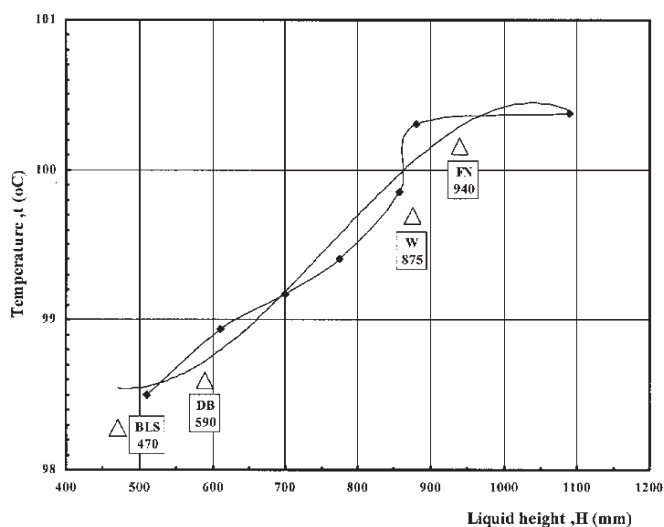


Fig. 7. The temperature profile at $q=7293 \text{ W/m}^2$ (water)

works have been written on this subject [13-21]. The tubes are classified as in [24]:

- microchannels (1-100) μm ;
- mezochannels (100-1000) μm ;
- macrochannels (1-6) mm;
- conventional channels $d_h > 6 \text{ mm}$

and according to [23]

- microchannels (10-200) μm ;
- minichannels (0.2-3) mm;
- conventional channels $d_h > 3 \text{ mm}$.

The flow boiling regimes observed within thermosyphon reboiler are as follows:

a) convection to liquid phase –this region at little thermal flux has a very long height, in order that at a high heat flux the height has a few centimeters;

b) bubbles are attached to the wall (BLS)-in this region to upward, over certain nucleation sites yield bubbles, but they leave not from surface to be fixed on active sites. The site of first bubble has the name of onset of nucleate boiling (ONB) point. Probably single contribution to heat transfer is the growth of transfer surface and condensation phenomenon to top of the bubble. This zone has different heights versus heat flux and principal heat transfer mechanism is convection. From references the region name is a partial subcooled flow boiling regime;

c) departure bubble region (DB)-here the bubbles leave from surface having a movement parallel to wall of glass tube sliding upward to a principal flow current where they

condense. The dimensional number for defining the surface point character, the first subcooling number N_{sub} and the second Zuber number is

$$N_{sub} = \frac{\Delta h_{sub,i}}{r_v} \cdot \frac{\Delta \rho}{\rho_g} ; \quad Zu = \frac{q \cdot P_h \cdot z_d}{w_{f,i} \cdot A \cdot r_v} \cdot \frac{\Delta \rho}{\rho_g \rho_f} \quad (17)$$

where:

Δh_{sub} –enthalpy difference of liquid boiling point and for liquid inlet;

P_h –tube perimeter;

$w_{f,i}$ –liquid velocity to inlet;

A –flow area; z_d –altitude of active site.

d) joint boiling zone (W) is a region where the production of vapour bubbles is very high in the first period the heat transfer surface is full covered by a bubble layer. In a section the two-phase mixture has form W. In this region the slope of temperature profile is modified. The low boundary of bubble layer is net vapour generation (NVG) point, from this point layer by layer of the bubbles advances to center line of the tube. From our experimental views boiling regimes observed this has a good compliance with classic presentations;

e) nucleate boiling (FN) –the region represents the first boiling regime at saturation state and his principal feature has yield little bubbles (few millimeters) and his dimensions rise to upward of the boiler tube. To the end of this zone a coalescence process is present at the same time appeared little Taylor bubbles. If the heat flux is low the position of this region is to the top of the boiler tube (about 1/4 of boiler length) and the temperature is approximately constant. In the risen heat flux his location go to down and in temperature profile appeared a maximum;

f) boiling churn flow (CF)-in this region the boiling has strong oscillations having indefinite aspect. The Taylor bubbles have large dimensions almost equal with pipe diameter, probably produced by coalescence. The temperature in the center line recedes to the saturation temperature at atmospheric pressure. A serie of steps were observed probably produced by axial dispersions.

g) annular boiling –this zone is observed to a maximum value of heat flux end its existence is not sure but in the temperature profile appears a temperature step. In figures (7) and (8) are given two representative temperature profiles obtained.

Conclusions

The experimental apparatus reproduces, inside a certain range, the functioning of industrial thermosyphon reboiler obtaining all boiling regimes without annular regime.

In all cases the rising temperature is in agreement with calculus data with respect to vapour pressure, for little heat flux temperature profiles appearing a landing (fig. 7), in final region.

At high heat fluxes appears a maximum, figure (8) of temperature profile and after this maximum some steps of temperature.

The changes slope of temperature profile and landings of temperature indicated a change of boiling region, figure (7) and (8).

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