ANALYSIS OF REVERSE FLOW IN LOW-RISE INVERTED U-TUBE STEAM GENERATOR OF PWR PACTEL FACILITY

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ABSTRACT

Previous experimental studies have shown that steam generator U-tube flow reverses during natural circulation in some U-tubes of inverted U-tube steam generators (UTSG) in pressurized water reactors. This study presents the results of three U-tube flow reversal experiments of the PWR PACTEL facility with a low-rise (1:4 height) inverted UTSG. An analytical model for a single-phase one-dimensional U-tube flow is used to explain the spatial distribution of the reverse flow in the U-tube bundle. In the experiments the reverse flow occurred in some of the longest U-tubes near the hot leg inlet. The experiments also show non-uniform temperature distribution in the hot plenum. In contrast, the calculations suggest that, the flow should have reversed in the shorter U-tubes, given uniform inlet temperatures. This contradiction is explained by the history of approaching the natural circulation conditions. During the start-up of the PWR PACTEL experiments, the loop flow increased from zero up, short U-tubes assumed the highest flow in the normal direction, eventually creating negative pressure drop, and thus forcing flow reversal in the longer U-tubes. The analysis also shows that the flow reversing should occur more likely in the U-tubes with lower inlet temperature. After the flow in first U-tubes reverses, the hot plenum temperature distribution becomes non-uniform, facilitating further flow reversal in nearby tubes. The flow reversal clusters to the U-tubes near hot leg inlet because mixing in the plenum is incomplete, and the U-tubes at the opposite side receive more hot water than the U-tubes on the inlet side.

KEYWORDS
PWR PACTEL, reverse flow, inverted U-tube, steam generator, natural circulation

1. INTRODUCTION

Natural circulation is an important physical phenomenon for the safety of the nuclear power plants. It is used to remove heat from the reactor core both in normal and accident conditions. Natural circulation is significant also for the proper operation of the passive safety systems utilized in nuclear power plants.

A natural circulation mass flow rate is always much lower than a forced flow in normal operating conditions. It has been shown in the experimental studies (e.g. [1], [2]) that at low net mass flow rates in inverted U-tube steam generators, the flow reverses in some steam generator U-tubes. The flow reversal is of safety significance because the U-tube flow returning from the cold plenum mixes with the flow coming from the hot leg, thus smoothing out potential initial differences in loop boric acid or noncondensable gas concentrations. The flow reversal does not affect the heat transfer in a steam generator as long as the whole U-tube bundle remains covered on the secondary side. The representative modelling of the U-tube flow reversal in computer code calculations (safety analyses) requires particular attention to the U-tube bundle nodalization.

The flow reversal is determined by the balance of the pressure drop characteristics i.e. frictional, acceleration, and gravitational loss in different U-tubes. The previous studies [1], [3] suggest that in the inverted U-tube steam generators the flow reversal should occur first in the longest U-tubes. However, Hao et al. [4] found that there exists a critical length of the U-tube. If all U-tube lengths of the tube bundle are shorter than the critical length, the flow reversing should occur first in the shorter U-tubes, and, if all the U-tube lengths are longer than the critical length, the flow reversing should occur first in the longer U-tubes. Hao et al. [5] investigated the influence of inlet fluid subcooling on the flow stability. They found that when the inlet subcooling is low, the flow reversing should occur more easily in the shorter length U-tubes, and when the inlet subcooling is high, the flow reversing should occur more easily in the longer length U-tubes.

In this study we present and analyze the results of the flow reversal experiments performed with the PWR PACTEL facility that has low-rise (1:4 height) inverted U-tube steam generators. In these experiments, the flow reversal was observed in some of the longest and intermediate length U-tubes. A steady-state analytical model for single-phase one-dimensional U-tube flow is used to explain the spatial distribution of reverse flow in the U-tubes. In particular, this study explains the apparent discrepancy between PWR PACTEL experiment results and the steady-state theory.

2. PWR PACTEL TEST FACILITY

The PWR PACTEL integral test facility [6] was designed and constructed in 2009 for safety studies related to the thermal hydraulics of the pressurized water reactors with vertical inverted U-tube steam generators such as in European Pressurized water Reactors (EPR). The general view of the PWR PACTEL test facility, the schematic view of the PWR PACTEL steam generator, and the arrangement of the U-tube bundle of the steam generator are presented in Fig.1.

The PWR PACTEL facility consists of a reactor pressure vessel model, two loops with the inverted U-tube steam generators, a pressurizer connected to one loop, and emergency core cooling systems. The pressure vessel is modelled as a U-tube construction representing a downcomer, a lower plenum, a core, and an upper plenum. The total height of the pressure vessel model corresponds to the pressure vessel height of the EPR plant. Both loops simulate one of the four reference EPR type primary loops, so half of the rated EPR capacity is simulated with the PWR PACTEL facility. The pressurizer is connected to the hot leg of the loop 2.

The height scaling in the PWR PACTEL steam generator is approximately 1:4 compared to the reference EPR type steam generator. The U-tube length versus the inner diameter (L/D) ratio for the PWR PACTEL steam generator U-tubes ranges between 373 and 456 (in the EPR plant the L/D ratio is about 1200). The U-tube bundle is located inside a riser volume, which is surrounded by an annular type downcomer. This downcomer is divided into hot and cold compartments. The lower riser area is also divided into hot and cold compartments by a divider plate, separating the hot and cold sides of the U-tube bundle. The compartments are not fully water tight, and therefore, minor cross flows can exist between the hot and cold parts.

The U-tube bundle contains 51 inverted U-tubes arranged in 10 rows. Table I presents the U-tube heights and lengths for each row. The inner and outer diameters of the U-tubes are 16.57 mm and 19.05 mm, respectively. Eight U-tubes in the steam generator 1 are instrumented with four primary fluid temperature measurements located at different positions. Fourteen U-tubes in the steam generator 2 are instrumented with more than one primary fluid temperature measurements, that is, either six, eight, or 13 measurement points. Fig. 1 shows the distribution of the instrumented U-tubes in the U-tube bundle of the steam generator 2.

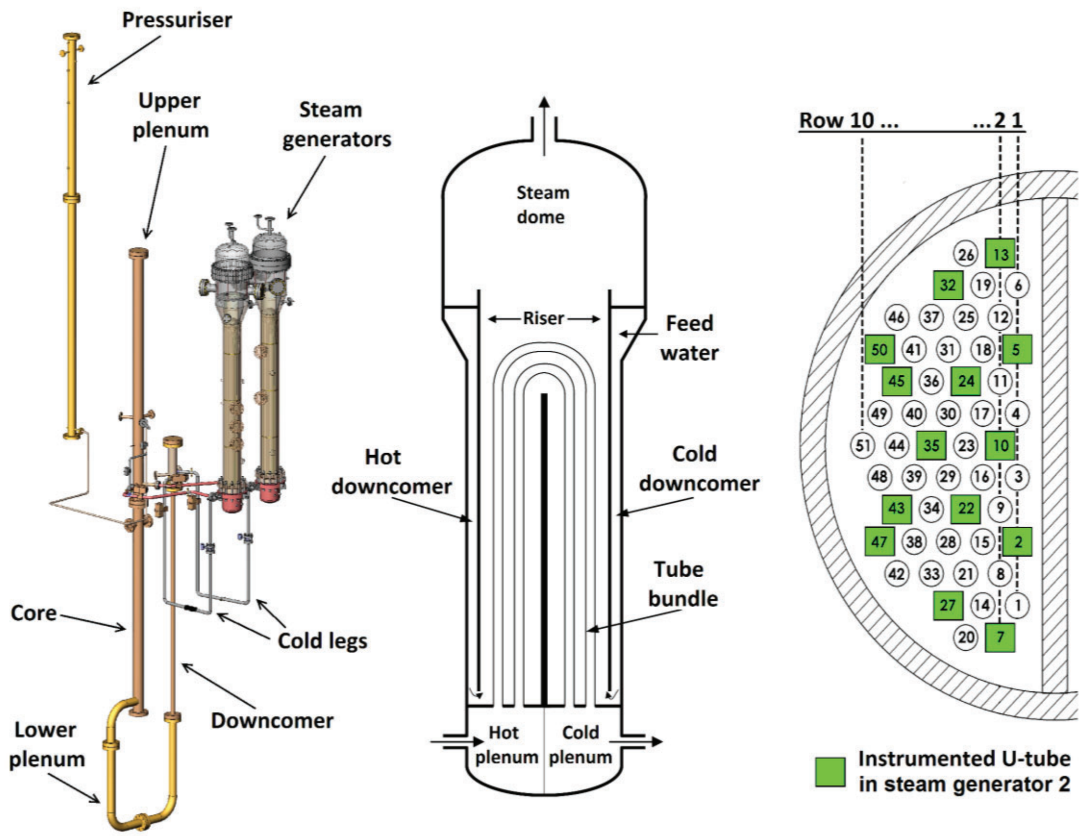

Figure 1. The general view of the PWR PACTEL facility, the schematic view of the PWR PACTEL steam generator, and the arrangement of the U-tube bundle.

Fig. 2 presents the geometry and the temperature measurement points of the hot and cold plenums in the steam generator 2. The hot and cold leg connections are located on the side of the plenums in horizontal orientation. The hot plenum of the steam generator 2 is instrumented with three temperature measurement points and the cold plenum with one temperature measurement point. Pressure difference measurement is provided to determine the pressure difference between the plenums. The loop to the plenum geometry of the reference steam generator is different from this model; the hot and cold leg connections are located on more at the bottom of the plenums on the side of the longest U-tubes and oriented at a 45-degree angle upwards.

Table I. The heights and lengths of the inverted U-tubes in the PWR PACTEL steam generator. The length ratio of the longest and shortest U-tube is 1.22.

Row	Number of U-tubes [-]	Height [mm]	Length [mm]
1	6	3076	6186
2	7	3090	6229
3	6	3226	6518
4	7	3240	6561
5	6	3377	6850
6	5	3391	6893
7	4	3526	7180
8	5	3540	7224
9	4	3676	7511
10	1	3689	7554

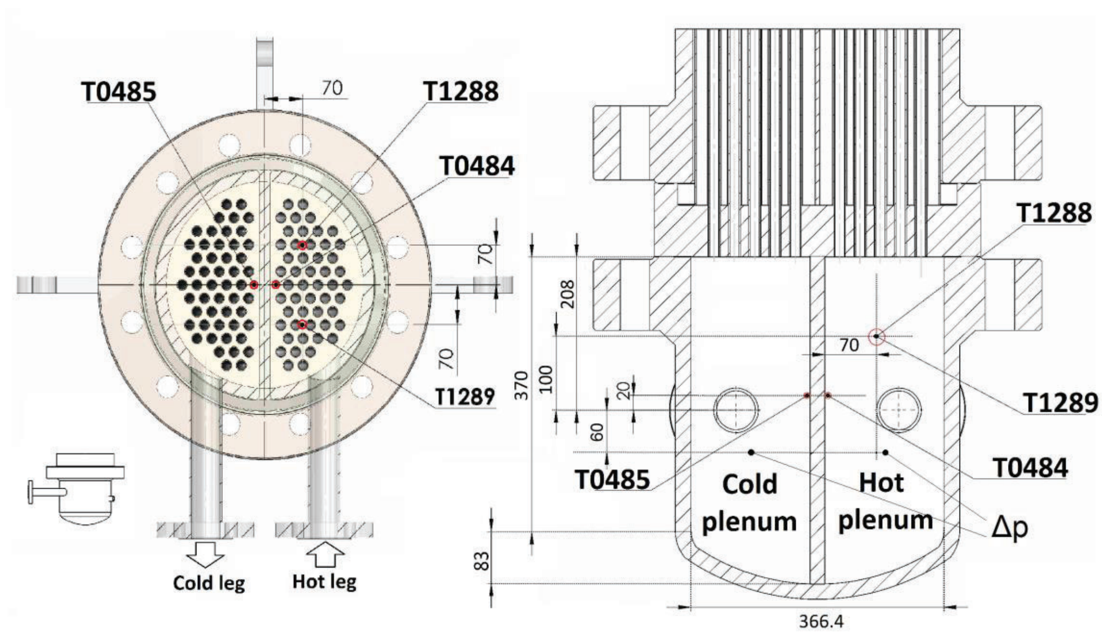

Figure 2. The temperature and pressure measurements in the hot and cold plenum in the PWR PACTEL steam generator 2.

3. REVERSE FLOW EXPERIMENTS OF PWR PACTEL

Three steady-state single-phase natural circulation reverse flow experiments [7] were carried out with the PWR PACTEL test facility in 2011. Table II presents the measured data of the experiments. The experiments RF-02 and RF-03 were carried out using only loop 2 and the experiment RF-04 using both loops. The primary side pressure was kept the same in all experiments. The secondary side temperature was varied between the experiments by changing the secondary side pressure. The whole U-tube bundle was wetted on the secondary side in all experiments.

The pressure difference between the hot and cold plenums was negative (i.e. the pressure in the hot plenum was lower than in the cold plenum) and the hot plenum temperature was much lower than the hot leg temperature in every experiment. This indicates that there was a strong reversed flow in some of the U-tubes. Based on mass and energy conservation in the hot plenum, the magnitude of the total reversed mass flow in the U-tubes is about the same as the hot leg mass flow while the total normal mass flow in the U-tubes is about two times bigger than the hot leg mass flow in every experiment. This can be deduced also from the observation that the hot plenum temperature is about halfway between the hot leg and secondary side temperatures. If the same mass flow rate is assumed in all U-tubes (regardless of the flow direction in the U-tubes), this means that the mass flow is reversed in about 1/3 of the U-tubes (17 of the 51 U-tubes).

Fig. 3 presents the flow directions in the instrumented U-tubes of the steam generator 2 in the experiments RF-02, RF-03, and RF-04. The flow inside a U-tube was assumed to be reversed when the temperature distribution along the U-tube was flat and close to the cold plenum temperature. According to Fig. 3, the flow in the shortest instrumented U-tubes in all experiments is into the normal direction, and the reversed flow occurs in the longer instrumented U-tubes. According to the measurements, the amount and locations of the U-tubes with reversed flow is almost the same in each experiment. This indicates that, within the range of the loop mass flow rate and secondary side temperature of the experiments, the amount of the U-tubes with reversed flow seems to be independent of the secondary side temperature and the loop mass flow.

Table II. Measured data of the reverse flow experiments.

Parameter	Unit	RF-02	RF-03	RF-04**
Loops included	[-]	1	1	2
Core power	[kW]	350 ± 6	600 ± 6	180 ± 6
Primary side pressure	[bar]	75 ± 1	75 ± 1	75 ± 1
Secondary side pressure	[bar]	20 ± 0.6	10 ± 0.6	40 ± 0.6
Loop mass flow	[kg/s]	1.11 ± 0.14	1.34 ± 0.14	0.68/0.63 ± 0.14
Pressure difference between the hot and the cold plenum	[Pa]	−262 ± 20	−399 ± 20	−135/−130 ± 20
Hot leg temperature	[°C]	277 ± 2	280 ± 2	277/276 ± 2
Hot plenum temperature*	[°C]	240–250 ± 2	220–240 ± 2	262–268 ± 2
Secondary side temperature	[°C]	213 ± 1	180 ± 1	250 ± 1
Cold plenum temperature	[°C]	216 ± 1	186 ± 1	250 ± 1

* Temperature range of three different measurement points

** Data from both loops (loop 1/loop 2) and steam generators (steam generator 1/steam generator 2)

It can be also concluded from Fig. 3 that the location of the hot leg inlet (marked with a black arrow) affects the flow reversing distribution in the U-tube bundle. The U-tubes with reversed flow are observed near the hot leg connection and the U-tubes with normal flow further away from the hot leg connection. The temperature measurements inside the hot plenum (T0484, T1288, and T1289 in Fig. 3) indicate that the temperature distribution inside the hot plenum is not uniform. The water temperature near the hot leg connection is lower than on the far side of the plenum. It is possible that the flow from the hot leg forms a turbulent jet that flows below the T1288 and T1289 measurement points hitting the wall at the far end of the plenum. The Reynolds numbers for the hot leg flow in the experiments RF-02, RF-03, and RF-04 are 280000, 350000, and 160000, respectively. This could explain that the hottest water flow temperatures from the hot leg are not measured with the temperature measurement point T1289 and that on the far side of the plenum the temperature (T1288) is higher. It is also likely that the reversed flow from the cold plenum decreases the temperature near the hot leg inlet.

The temperature distribution in the hot plenum can be examined in more detail with the lowest U-tube temperature measurements. Fig. 3 shows the U-tube inlet temperatures at the beginning (at the elevation of +0.3 m from the U-tube inlet) of each instrumented U-tube. In the U-tubes with the reversed flow the temperatures are very close to the secondary side temperatures. In the U-tubes with the normal flow the temperatures range from 239 to 249 °C in RF-02, from 222 to 238 °C in RF-03, and from 261 to 265 °C in RF-04. The lowest temperatures are measured in the short U-tubes with the inlet location near the hot leg inlet and the highest temperatures in the U-tubes with the inlet location on the far side of the plenum.

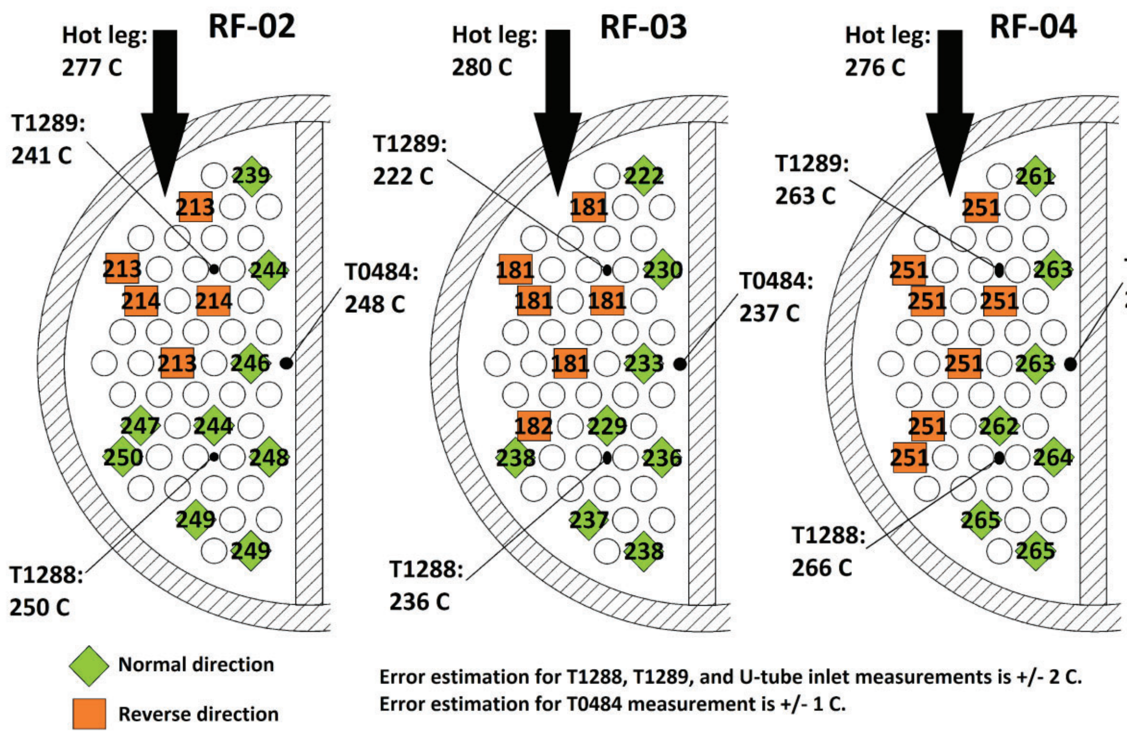

Figure 3. Flow direction and measured temperatures inside the instrumented U-tubes and the hot plenum of steam generator 2 in the experiments RF-02, RF-03, and RF-04. The black arrow indicates the flow direction from the hot leg. The U-tube temperatures are measured at the level of 0.3 m with the exception of the U-tubes 22 and 43 in which they are extrapolated from the level of 0.7 m.

4. ANALYTICAL MODEL

We use a steady-state analytical model for a single-phase one-dimensional U-tube flow to interpret the experiment data. The model considers only a single U-tube system with the inlet and outlet boundary conditions. It does not take into account the lateral-closed multi-channel system as a calculation domain. The model is based for most part on the model created previously by Jeong et al. [3]. In addition, here the heat transfer coefficient U and the friction factor f are modelled as a function of the Reynolds number (mass flow). The U-tube bend is included in the height of the U-tube, and the local resistance of the bend is considered. The water properties are determined at the average temperature of the U-tube flow.

The momentum conservation equation for a vertical one-dimensional U-tube flow can be written as:

$$\rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}\right)=-\frac{\partial p}{\partial x}-\frac{f}{d_i}\frac{\rho v^2}{2}\pm g\rho \quad (1)$$

where ρ is the density of the fluid [kg/m^3], v is the velocity of the fluid [m/s], p is the primary pressure [Pa], g is the gravitational acceleration [m/s^2], d_i is the inner diameter of the U-tube [m], f is the friction factor of the U-tube wall, t is time [s], and x is the coordinate [m] along the U-tube in the normal flow direction. The ± sign before the gravitation term means a negative sign for the hot side and a positive sign for the cold side of the U-tube.

By integrating Eq. (1) from the U-tube inlet to the U-tube outlet, assuming steady-state conditions, neglecting the spatial acceleration term, and replacing the velocity v with the mass flow rate $q_m = \rho v A$ in the friction term, the pressure difference between the inlet and outlet plenum can be written as follows:

$$\Delta p=(p_{in}-p_{out})=\left(\frac{fL}{d_i}+K\right)\frac{q_m^2}{2\bar{\rho}A^2}-g(\bar{\rho}_c-\bar{\rho}_h)H \quad (2)$$

where L is the length of the U-tube [m], K is the local form loss of the U-tube bend [-] (calculated from $K = 0.262+0.326(d_i/r_b)^{3.5}$ [8] where r_b is the bending radius [m]), H is the height of the U-tube [m], and A is the cross-sectional area of the U-tube [m^2].The terms $\bar{\rho}_h$ and $\bar{\rho}_c$ are the average densities of the hot and cold sides of the U-tubes, respectively, and $\bar{\rho}$ is the average density over the whole U-tube length.

Water density is expressed as a function of temperature according to the Boussinesq approximation, as follows:

$$\rho(T)=\rho_0[1-\alpha(T-T_0)] \quad (3)$$

where α is the thermal expansion coefficient of the fluid [1/K], ρ_0 is the reference density [kg/m^3], and T_0 is the reference temperature [K]. In this case T_0 is the secondary side temperature and ρ_0 the density at the operation pressure and the reference temperature.

The cooling of the fluid in the U-tube equals the heat transfer through the U-tube wall, so the steady-state energy balance for a differential element dx can be expressed as follows:

$$-q_m c_p dT_{pri}=2\pi r_o U\left(T_{pri}-T_{sec}\right)dx \quad (4)$$

where c_p is the specific heat capacity [J/kgK], r_o is the U-tube outer radius [m], U is the total heat transfer coefficient through the U-tube wall [W/m^{2}K], and T_{pri} is the primary side temperature [K] and T_{sec} the secondary side temperature [K]. By integrating Eq. (4), the temperature distribution of the fluid along the U-tube is obtained as follows:

$$T_{pri}(x) = T_{sec} + \left(T_{pri,inlet} - T_{sec}\right)exp\left(-\frac{2\pi r_o U}{c_p q_m}x\right) \tag{5}$$

The average densities can be calculated by using Eq. (3) with average temperatures, which are obtained by integrating Eq. (5) over the U-tube length. Then, Eq. (2) can be expressed as follows:

$$\Delta p = \left(f\frac{L}{d_i} + K\right)\frac{q_m^2}{2\overline{\rho}A^2} - \frac{g\rho_0\alpha c_p q_m}{2\pi r_0 U}\left(T_{pri,inlet} - T_{sec}\right)\left(1 - exp\left(-\frac{2\pi r_o U}{c_p q_m}H\right)\right)^2 \tag{6}$$

The first term on the right side is the friction term and the second term on the right side is the gravitation term.

The total heat transfer coefficient *U* is calculated as follows:

$$U = \frac{1}{\frac{1}{\alpha_i}\frac{r_o}{r_i} + \frac{ln\left(r_o/r_i\right)r_o}{k_p} + \frac{1}{\alpha_o}} \tag{7}$$

where r_i is the U-tube inner radius [m], α_i and α_o are the heat transfer coefficients inside and outside of the U-tube wall [W/m^{2}K], respectively, and k_p is the heat conduction of the U-tube wall.

The Nusselt number is calculated from Gnielinski correlation [9] for turbulent and transition flow zone (Re > 2300) from:

$$Nu_D = \frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)^{1/2}\left(Pr^{2/3}-1\right)} \tag{8}$$

where *Re* is the Reynolds number and *Pr* is the Prandtl number. When $Re < 2300$, the Nusselt number is a constant with the value of *3.66*. The friction factor *f* for smooth surface is calculated from the correlation of Petukhov [9], when $Re > 2300$, as follows:

$$f = \frac{1}{(0.790\ln(Re)-1.64)^2} \tag{9}$$

In the laminar zone (Re < 2300) the friction factor is calculated as follows:

$$f = \frac{64}{Re} \tag{10}$$

The outer wall heat transfer coefficient α_o [W/m^{2}K] is calculated from the correlation of Thom [10] as follows:

$$\alpha_0 = 1971.2exp\left(\frac{2p}{8687000}\right)\left(T_w - T_{sec}\right) \tag{11}$$

where *p* is the secondary side pressure [Pa] and T_w is the wall temperature on the secondary side [K]. The wall temperature T_w is assumed to be $T_{sec}+5$ °C.

5. ANALYSIS OF THE FLOW REVERSING EXPERIMENTS OF PWR PACTEL

By using Eq. (6), the total pressure drop can be plotted as a function of the mass flow rate giving a characteristic curve of the U-tube. In Fig. 4 the characteristic curve with the friction and gravitation terms is plotted for the shortest and the longest U-tube of the PWR PACTEL steam generator in the conditions of the experiment RF-02 and at the uniform inlet temperature of 245 °C. The characteristic curves of the medium height U-tubes lie between the shortest and the longest U-tube.

The friction term decreases monotonically when the mass flow rate in the U-tube decreases, as can be seen in Fig. 4. The gravitation term is a more complicated non-monotonic function that depends on the average densities of the hot and the cold side of the U-tube. Unlike the friction term, the gravitation term causes a negative pressure drop between the hot and the cold plenum. The fluid temperature decreases exponentially along the U-tube (Eq. (5)), meaning that with a normal flow direction, a hot water column will mostly appear on the hot side of the U-tube and the average density on the hot side is lower than on the cold side. The height of the hot water column depends on the mass flow rate of the U-tube and the temperature difference between the primary and secondary side. With the decreasing mass flow rate in the U-tube, the hot water column and the negative gravitation pressure drop decreases. With the increasing mass flow rate, the hot water column will increase and eventually reach the cold side of the U-tube or even the cold plenum. Consequently, the difference of average densities between the hot and the cold side of the U-tube decreases, and the negative gravitation pressure drop will approach to zero.

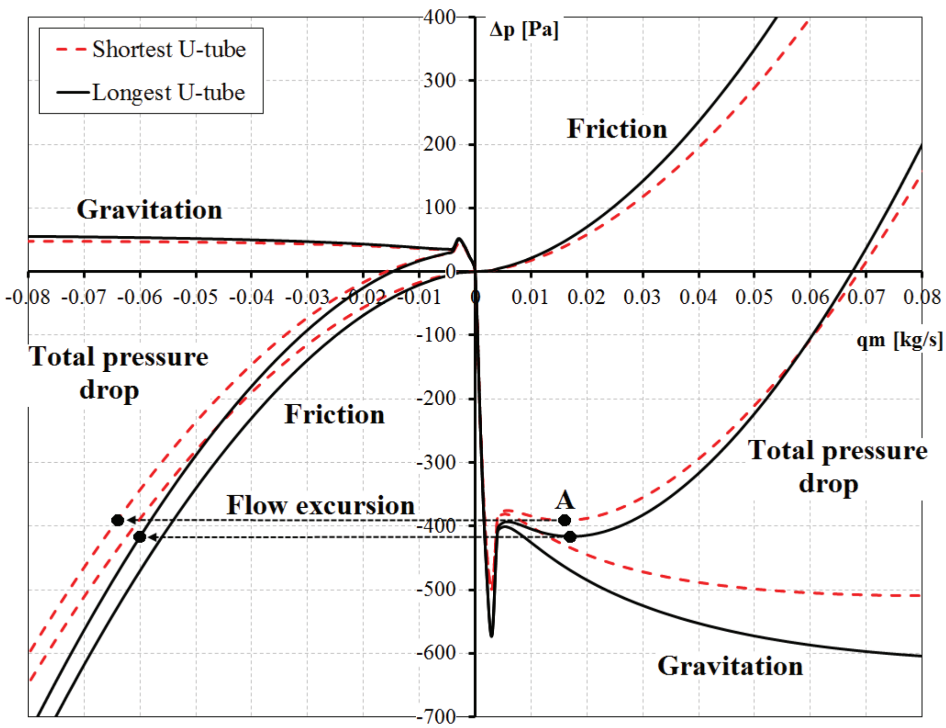

Figure 4. The total pressure drop and the friction and gravitation pressure drops as a function of mass flow in the shortest and the longest U-tube of the PWR PACTEL steam generator in the conditions of RF-02 experiment and at the uniform inlet temperature of 245 °C (average temperature of hot plenum).

Because of the combined effect of the friction and the gravitation terms, the characteristic curve (total pressure drop) is also a non-monotonic function of the mass flow rate. It has a negative slope and a minimum point (point A in Fig. 4) at certain low flow conditions. As shown in Fig. 4, the positive flow can exist even when the total pressure drop between the hot and the cold plenum is negative. There is a the minimum point (called a critical pressure drop in this paper) at which decrease in the pressure drop will push the flow to the unstable region and a flow excursion occurs in the U-tube turning the mass flow into the negative (reversed) direction.

In the unstable region a fast drop (Fig. 4) in the gravitation term near the zero flow (mostly in the laminar flow zone) is a consequence of the reduced heat transfer coefficient inside a U-tube wall. The Nusselt number drops rapidly to the constant value of 3.66 at the start of the laminar zone ($Re < 2300$). This increases rapidly the water temperature decreasing the water density on the hot side of the U-tube and causing the fast drop in the gravitation term. In the laminar zone, the Nusselt number stays constant while the mass flow still decreases and the gravitation term increases to zero. In practice, the gravitation term reacts with a delay because the changing of the water content of the U-tube takes time. Consequently, the temperature distribution in the U-tube does not change immediately, and the flow excursion occurs before a new temperature distribution inside the U-tube has time to form. The friction term reacts immediately to the flow changes because it depends on the flow velocity.

In the negative flow zone, the gravitation term is usually near zero, because the cold plenum temperature is usually close to the secondary side temperature, and the friction term dominates. In the experiment RF-02 the temperature in the cold plenum was 3 °C higher than on the secondary side. Hence, in Fig. 4 the gravitation term is positive, and the characteristic curve is above the curve of the friction term.

According to Fig. 4, the critical pressure drop in the geometry of the PWR PACTEL facility is higher in the shortest U-tube. The flow in the shortest U-tube should reverse before the flow in the longest U-tube when the pressure drop decreases between the hot and cold plenums. It can be seen that the characteristic curves of the shortest and the longest U-tube cross when the mass flow rate inside the U-tubes is near 0.06 kg/s, and the total pressure drop become less negative in the shortest U-tube than in the longest U-tube. The reason for this crossing is that the hot water column in the shortest U-tube reaches the cold side further than in the longest U-tube, reducing the driving gravity head more in the shortest U-tube than in the longest U-tube. The mass flow rate in the U-tubes is so low that the friction pressure losses are almost the same for both U-tubes. Therefore, the gravitation term dominates, and the total pressure drop difference between the shortest and longest U-tubes is generated almost totally by the gravitation difference. This can be clearly seen from the friction and gravitation terms in Fig. 4. The crossing occurs when the difference of the friction pressure drop between the shortest and the longest U-tube becomes smaller than the difference of the gravitation pressure drop between the shortest and the longest U-tube.

With the high steam generators, at low flow conditions, the hot water column inside any of the U-tubes will not reach the cold side as easily as in the low-rise steam generators. The gravitation terms in all U-tubes in high steam generators are almost same while there are still differences in the friction pressure drops between the short and long U-tubes. Hence, the total pressure drop difference between the short and long U-tubes is mainly a result of the friction term, which is always higher in the longer U-tubes.

Fig. 5 presents the characteristic curves for the shortest and the longest U-tube in the conditions of the experiments RF-02, RF-03, and RF-04. The hot leg temperature is now used as the U-tube inlet temperature because in forced flow conditions all the U-tubes should be in normal direction and the U-tube inlet temperatures should be the same as the hot leg temperature. According to Fig. 5, in all experiments the characteristic curve of the shortest U-tube lies above the characteristic curve of the longest U-tube. Thus, in the PWR PACTEL facility the flow reversing should occur first in the shortest U-tubes.

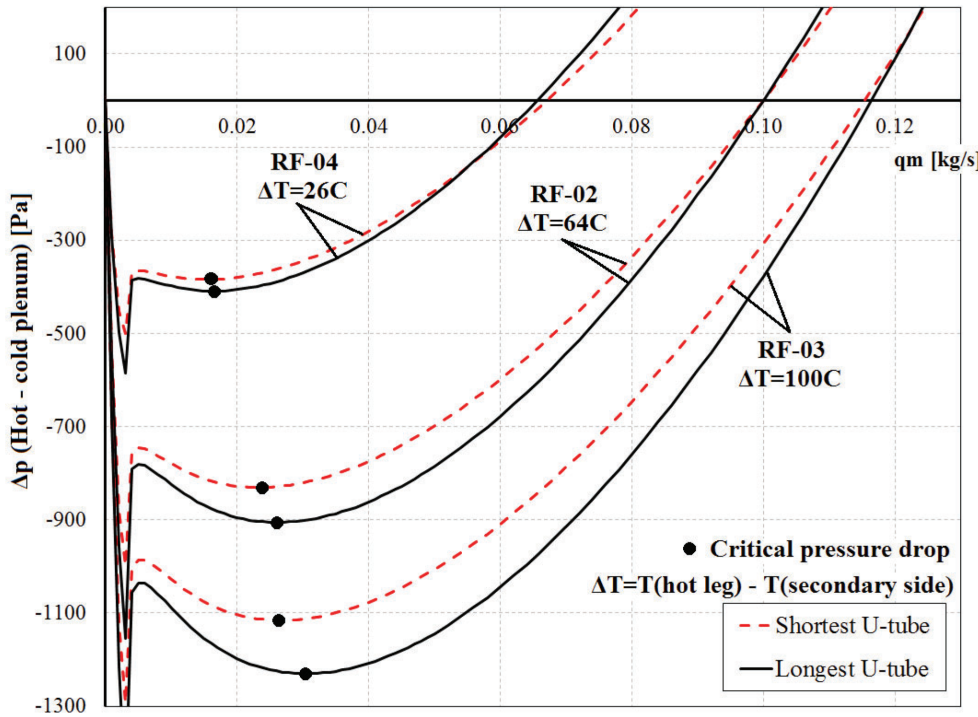

Figure 5. The characteristic curves for the shortest and the longest U-tube in the conditions of the experiments RF-02, RF-03, and RF-04 and at the uniform inlet temperature (hot leg temperature) of 277 °C, 280 °C, and 276 °C, respectively. According to these characteristic curves, the short U-tubes should have been reversed, whereas in the experiment reversed flow was observed in the long U-tubes.

Fig. 4 and 5 present the characteristic curves assuming the uniform U-tube inlet temperature for all U-tubes. As was seen from Fig. 3, in the experiments the temperature distribution inside the hot plenum is not uniform and the temperature differences between the U-tubes are relatively large. Fig. 6 presents the effect of the U-tube inlet temperature on the characteristic curves of the medium length U-tubes. By decreasing the inlet temperature of the U-tube by 5 °C in the experiment RF-02, RF-03, and RF-04 conditions, moves the characteristic curve of the U-tube upwards by 50 to 100 Pa. Thus, relatively small differences in the inlet temperature can change the order of reversal. The reason for this can be found again in the average densities on the hot and cold sides of the U-tubes. Due to the lower inlet temperature, the average density on the hot side of the U-tube is higher and the gravitation pressure drop is less negative. As a result, the characteristic curve of the U-tube is less negative and the flow in the U-tube will more likely to reverse.

In real nuclear power plants, the natural circulation conditions are usually approached from forced flow conditions where the mass flow rates are clearly higher than during the natural circulation conditions. With the high loop mass flow rates there is a normal flow in every U-tube and the hot plenum temperature is uniform being the same as the hot leg temperature. When the loop mass flow rate is decreasing (i.e. after a main coolant pump trip) and the pressure difference between the plenums becomes negative, the first U-tubes where flow reversal occurs, should be determined according to the U-tube length. According to the analysis presented here, in the PWR PACTEL facility the first reversing U-tubes should be the shortest U-tubes. Yet, in the experiments the reversed flow was observed in the longer U-tubes.

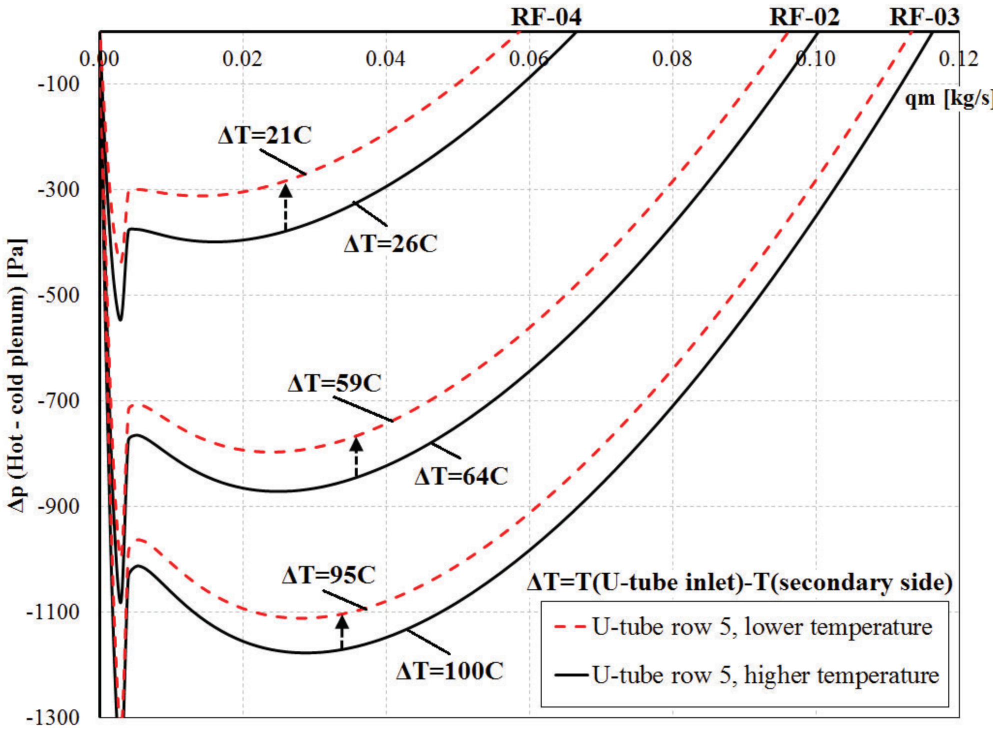

Figure 6. The characteristic curves for the medium length U-tube with different inlet temperatures in the conditions of the experiments RF-02, RF-03, and RF-04. Notice that with lower inlet temperature, the flow in the U-tube is less stable enabling the flow reversal in it more easily.

There were no pumps installed in the PWR PACTEL facility during these flow reversal experiments. The natural circulation conditions were approached by increasing the loop mass flow rate from the zero by increasing the core power. Data of this heat-up period of the experiments was not recorded.

In the PWR PACTEL experiments, the heat-up begins from the uniform room temperature around the facility. In the beginning of the heat-up, the water temperature is uniform and there are no density differences or gravity head in the steam generator. At the start-up, when the core power is increased, the hot water starts to flow into the steam generator. The mass flow is now higher in the shortest U-tubes than in the longest U-tubes because the friction resistance is smaller in the shortest U-tubes.

The negative pressure difference between the plenums forms only after the warmer water reaches the U-tubes. Now, because of the higher mass flow rate, the average density is lower on the hot side of the shortest U-tube than on the hot side of the longest U-tube. Consequently, the negative gravitation pressure drop is higher in the shortest U-tube than in the longest U-tube. Hence, the critical pressure drop is less negative and the U-tube flow is more likely to reverse in the longest U-tube. Thus, in the start-up of the flow reversal experiments, the flow reversal can occur in the longer U-tubes. As shown above, the first U-tube with reversed flow makes the nearby U-tubes more likely to reverse by bringing cold water to their inlet. This explains why the U-tubes with reversed flow accumulate in the longest and intermediate U-tubes in the PWR PACTEL experiments.

The non-uniform temperature distribution in the hot plenum also explains why in a set of equally long U-tubes the flow could go either way and the U-tubes with the reversed flow are located near the hot leg inlet. According to Fig. 3, in every experiment the plenum temperature was lower near the hot leg inlet and higher at the far side of the plenum. The analytical calculations (Fig. 6) suggest that the flow in the U-tubes should reverse more easily in the U-tubes where the inlet temperature is lower. Therefore, the flow in the U-tubes near the hot leg inlet should experience the flow reversal more easily than on the far side of the plenum where the plenum temperature was higher and the flow in the U-tubes more stable. If the flow reversing does not occur in all U-tubes at the same time, the first reversing U-tubes make the temperature distribution in the hot plenum non-uniform, which then affects the location of later reversing U-tubes. The later reversing U-tubes should therefore locate more likely near the hot leg inlet where the temperature is lower.

In conclusion, the U-tube pressure drop characteristics can adequately explain the U-tube behavior of the PWR PACTEL steam generators. More accurate treatment would necessitate modelling of the plenum but too little experiment data is available at present.

6. CONCLUSIONS

The results of the three flow reversal experiments of the PWR PACTEL facility with low-rise inverted U-tube steam generators were presented. A steady-state analytical model for a single-phase one-dimensional U-tube flow was used to explain the spatial distribution of reverse flow in the inverted U-tube bundle of the PWR PACTEL facility.

In the PWR PACTEL flow reversal experiments the flow in the shortest U-tubes was in all experiments into the normal direction and the reverse flow occurred in the longer U-tubes near the hot leg inlet. The experiments indicate a non-uniform temperature distribution in the hot plenum. Near the hot leg inlet the temperature was lower than on the far side of the plenum. It was concluded that the temperature distribution in the hot plenum was a consequence of cold water flow from the reversed U-tubes and hot water flow from the hot leg injection. The location of hot leg connection was assumed to have an influence to the non-uniform temperature distribution.

The calculations suggest that, given uniform inlet temperatures, the flow should reverse first in the shorter U-tubes in the PWR PACTEL steam generator which is inconsistent with the experiment results. The history of how the natural circulation conditions are approached could explain the difference between the calculation and experiment results. In real nuclear power plants, the natural circulation conditions are usually approached from forced flow conditions where the mass flow rates are clearly higher than during the natural circulation conditions. In the PWR PACTEL facility the natural circulation conditions were approached by increasing the loop mass flow rate from zero to the desired level by increasing the core power. During the start-up of the experiments, the flow reverses first in the longer U-tubes. When the loop flow increases from zero up, the short U-tubes have the highest flow in the normal direction because the friction resistance is smaller. This higher flow creates the higher negative gravitation pressure drop in the shorter U-tubes because of the lower average density in the hot side of the U-tube, and thus forces the flow reversal to occur in the longer U-tubes.

It was also concluded that the temperature distribution in the hot plenum could explain why in a set of equally long U-tubes the flow could go either way and the U-tubes with the reversed flow are located near the hot leg inlet. In every experiment the plenum temperature was lower near the hot leg inlet and higher at the far side of the plenum. The analysis suggests that with the lower inlet temperature, the U-tube flow is less stable and should experience the flow reversal more easily than with the higher inlet temperature. The lower inlet temperature increases the average density on the hot side of the U-tube causing the gravitation pressure drop along the U-tube became less negative and the flow in the U-tube less stable. The non-uniform temperature distribution in the hot plenum is a consequence of the reversed cold water flow from the U-tubes. It could be possible that the flow reversing does not occur in all U-tubes at the same time and that the later reversing U-tubes are centered more likely near the already reversed U-tubes and near the hot leg connection where the plenum temperature is lower.

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