PEACH BOTTOM BWR TURBINE TRIP BENCHMARK: PSI ANALYSIS OF EXERCISE 1 USING RETRAN-3D

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ABSTRACT

This paper presents the results of the calculation of exercise 1 of the Peach Bottom Unit 2 Turbine Trip Test 2, OECD/NEA BWR benchmark for coupled thermal hydraulics and neutronics codes. To simulate the plant system the transient is calculated here using the RETRAN-3D code with the predefined power versus time obtained from the experimental data. The PSI-RETRAN-3D model gives good agreement with the measured data. In order to determine the important physical process in this transient we have investigated the sensitivity of the calculations to the modeling of the steam separator/downcomer region, and show that this is crucial to predict the measured pressure increase during the first 2 sec, and in particular around the time of the maximum power at 0.7 sec. Changes in the turbine bypass line also influence the pressure in the steam dome, however not until after 2 sec. To examine the sensitivity of the results to the system nodalization and physical modeling, we compare the effects of re-nodalizing the steam separator region, of using the 4-equation and the 5-equation model, of using a two-region non-equilibrium model, and changing the steam separator inertia. For the case considered the re-nodalization of the steam separator and the use of the two-region non-equilibrium model provide the largest improvement in the prediction of the steam dome pressure. Using the 5-equation model or changing the inertia in the steam separator region shows only a small effect.

1. INTRODUCTION

The Peach Bottom Unit 2 Turbine Trip Test 2 (PB2 TT2) was selected by OECD/NEA as a BWR benchmark for coupled thermal hydraulics and neutronics codes [1]. This benchmark is being performed in three parts (exercise 1, 2 and 3) and the results for exercise 1 are presented here. Benchmarks of this form are very helpful in assessing the capability of coupled codes to analyze complex transients with coupled core-system interactions. This paper presents the results of exercise 1 using the RETRAN-3D code [2] to simulate the plant system with the reactor power taken from the experimental data. We analyze a base case and perform sensitivity studies to examine the influence of the system nodalization and physical modeling on the prediction of the steam dome pressure. Our results for exercise 2 calculated using the CORETRAN code are presented in a companion paper [3].

2. THE RETRAN-3D BASE MODEL

The RETRAN-3D input model for exercise 1 was developed from an early RETRAN-02 model for turbine trip 1 [4]. From this model we used the nodalization of the reactor vessel including the steam separator and downcomer region, the re-circulation loop and the steam lines. The reactor core region was re-nodalized (including the accompanying heat structures), to include 24 axial control volumes, in combination with a core exit volume and a core inlet volume that is connected to the core bypass volume.

From the benchmark specification [1] we used the time dependence and axial profile of the pre-defined power, together with the feedwater flow, the turbine inlet flow rate and the turbine bypass area. Also the enthalpy in the steam dome, the dome pressure and the flow rates at t = 0 were used. Finally for the base case the RETRAN-3D code options of the 4-equation model (thermal equilibrium) and the Zolotar-Lellouche slip correlation were applied. Note that for the pressures considered here (>6.0 MPa) the Zolotar-Lellouche slip correlation is shown [5] to give good agreement with steady-state void fraction experimental measurements.

The base case, in general, is in good agreement with the measured pressure as represented by the steam dome relative pressure (Figure 1). The calculation shows the initial increase in the pressure as the pressure wave propagates along the steam line from the turbine, followed by the pressure increase as the power increases, between 0.5 and 0.9 sec, and later the oscillations due to the pressure wave in the steam line, with a periodicity of a little below 1 sec. The flattening of the curve after about 3 sec and the beginning of the decrease as a consequence of the power reduction is also calculated.

The initial increase in the measured pressure at about 1 sec, which is due to the closure of the turbine stop valve and the power increase is larger than the calculated one, by about 0.1 MPa, while after 1 sec, both curves are almost parallel. In order to investigate the possible reasons for the discrepancy in the initial pressure rise we looked at two features of the plant representation and physical modeling. This was based upon the knowledge that the system pressure is dependant upon the energy (steam) production/conservation in the vessel and the pressure loss along the steam line.

When we increase the pressure losses in the turbine bypass line, then the steam dome differential pressure at times greater than 3 sec is also increased (Figure 1a). Up to 2 sec however, there is no visible effect on the steam dome pressure, and the increased pressure rise at about 1 sec in particular is not captured. Thus the reason for this increased rise is not in the turbine bypass line. This is, because changes in the turbine bypass pressure losses only influence the steam dome pressure first after the turbine bypass is nearly full open and a "steady-state" flow along the steam line is established.

Since the pressure increase after 0.5 sec is driven primarily by the additional steam production, which comes from the power increase, it is important to determine the distribution including any condensation of this steam as it flows through the steam separators into the steam dome and upper downcomer regions.

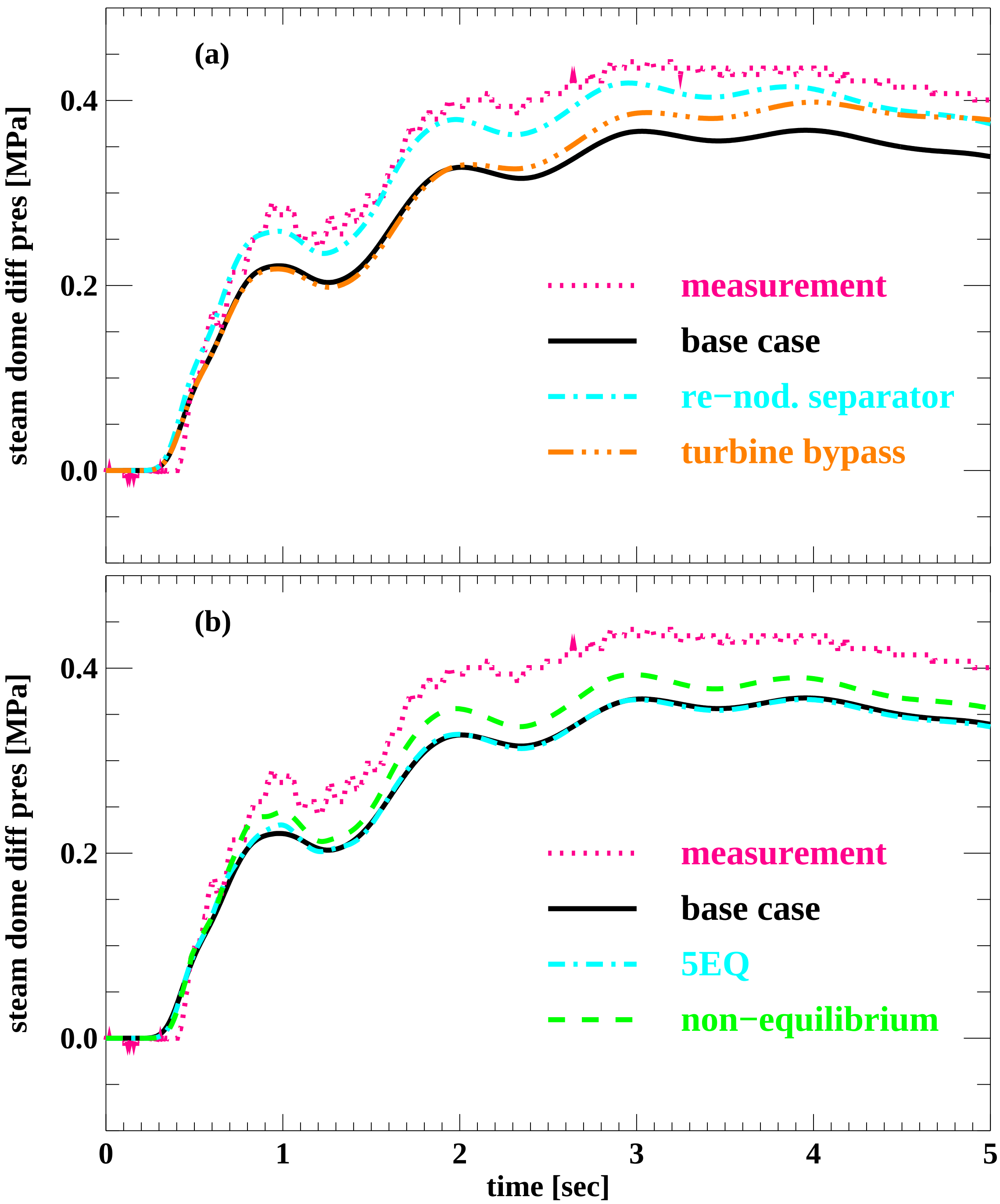

Figure 1: Steam dome differential pressure versus time – variations of the base case.

3. INVESTIGATION OF THE IMPACT OF NON-EQUILIBRIUM EFFECTS

3.1 NODALISATION OF THE STEAM SEPARATOR REGION

In order to determine the distribution of the steam flow it is important to follow the flow of steam through the separators into the steam dome [6]. In the reactor, two-phase flow from the core region passes through the standpipes and enters then the steam separators. In each separator, the steam-water mixture passes turning vanes, which impart a spin to establish a vortex, which separates the water from the steam. The denser liquid is thrown radially outward by centrifugal force forming a continuous film on the inside wall of the inner pipe. The separator water exits from under the separator cap and flows out between the standpipes, draining into the downcomer. Steam with a quality of at least 90% exits from the top of the separator and rises to the dryers. The dryers force the wet steam to be directed horizontally through the dryer panels. The steam is forced to make a series of rapid changes in direction while traversing the panels. During these direction changes the heavier drops of entrained moisture are forced to the outer walls where moisture collection hooks catch and drain the liquid to collection troughs, then through tubes into the vessel downcomer, so that the steam dryer assembly increases the quality of the steam to more than 99.9%. This dry steam flows into the steam dome and into the steam lines.

This behavior is approximated in the RETRAN-3D model by control volumes (CV 1-5 in Figure 2). Two-phase flow from the core region flows into the steam separator volume (CV 1). In this volume a liquid level is defined below which two-phase flow is established, while above the level there is only steam flow. In this volume (CV 1) the RETRAN-3D bubble rise model option is used. The steam flow is upwards to the lower dryer volume (CV 2) and continues to the steam dome volume (CV 3) and into the steam line. Two-phase flow consisting of water with some vapor carryunder flows from the steam separator volume to the steam separator external volume (CV 4). The junction between these two control volumes is below the liquid level in CV 1. In the steam separator external (CV 4) a liquid level develops with a steam phase above the liquid level and a two-phase region below the level. The RETRAN-3D bubble rise model is again used to describe this phenomenon. At $t = 0$ there is a very small steam flow from the steam separator external to the lower dryer volume (CV 2), while the main flow is water down into the upper downcomer (CV 5). The feedwater also flows into the upper downcomer volume. From there, water flows to the lower downcomer and the jet pumps and from there back into the core.

Since the RETRAN-3D code option used in this analysis is that of the 4-equation model (ie full thermal equilibrium), the volume of water in the steam separator (CV 1) and steam separator external (CV 4) two-phase control volumes is in equilibrium with the steam, and this will strongly influence the pressure increase per unit of steam generated in the core. For this reason a re-nodalization of the separator/downcomer region (Figure 2) was performed which is shown to give a pressure increase equal to the measured one at about 1 sec (Figure 1a). In order to achieve this, the volumes of the steam separator and the steam separator external control volumes were reduced, while the volume of the upper downcomer control volume was increased to preserve the total volume of water.

The main effect of the re-nodalization is a reduction in the energy transfer from the gas phase to the liquid phase, because the volume is smaller within which thermal equilibrium is established. Thus there is less condensation of the vapor as the pressure increases. To obtain the measured pressure increase it was necessary to approximately half the volume of the steam separator and the steam separator external control volumes.

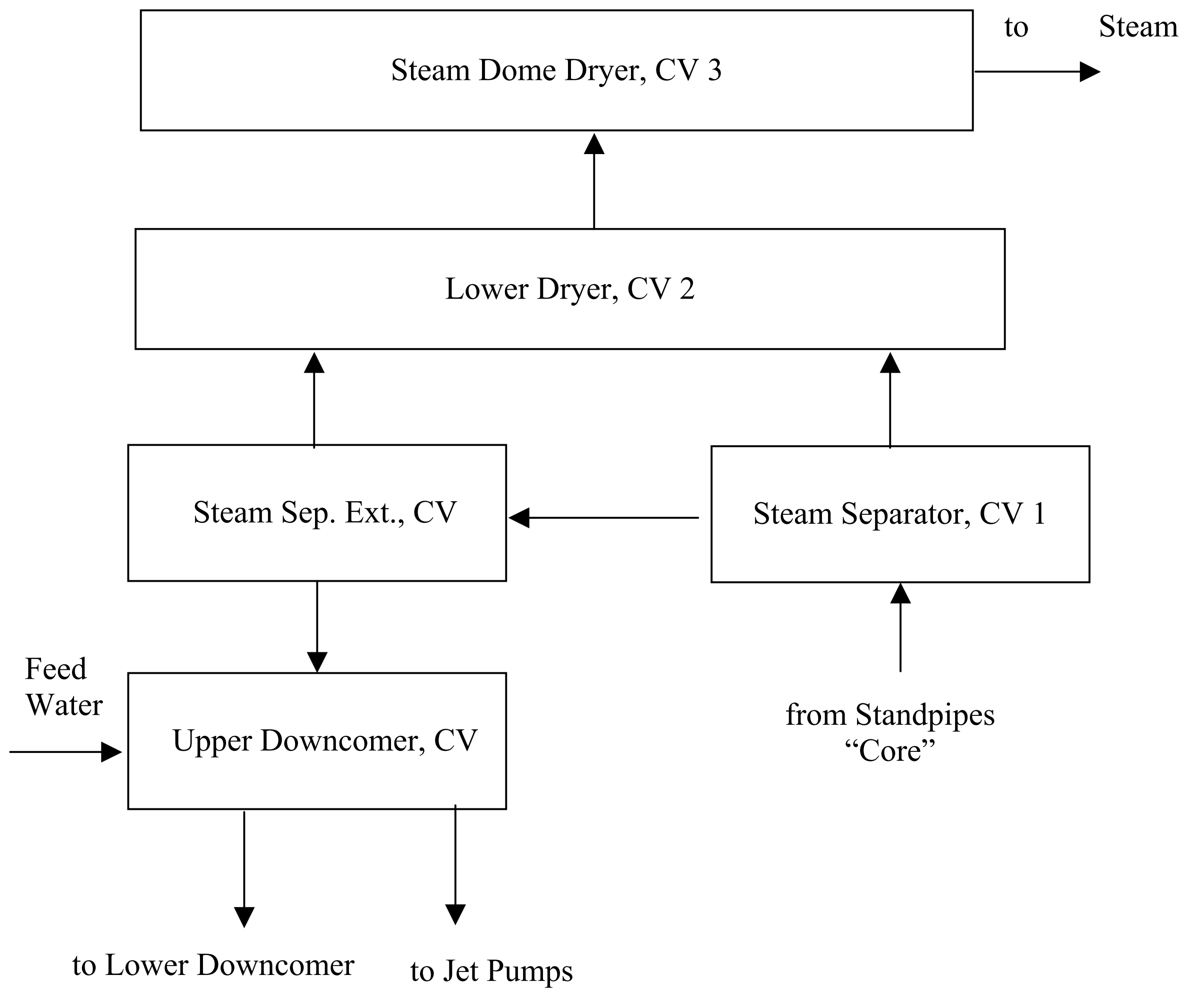

Figure 2: Nodalization diagram of the steam separator / downcomer region.

3.2 TWO-REGION NON-EQUILIBRIUM MODEL

Another RETRAN-3D code option that can be used to obtain a reduced energy transfer between the liquid and the vapor region is the "two-region non-equilibrium model" [2] [A. Olson, private communication, 2001]. In this model RETRAN-3D divides the fluid in the control volume at the liquid level interface into two regions, where each region is in internal thermal equilibrium, but the two-regions are not necessarily in equilibrium with each other. The "liquid" region below the interface and the "vapor" region above the interface have the same pressure, but in general have different temperatures, ie in the vapor region for example we may have superheated steam. The application of this model (in the steam separator volume and the steam separator external volume, CVs 1 and 4 in Figure 2) also produced an increased pressure rise at about 1 sec (Figure 1b). A sensitivity study showed that the effect in the steam separator volume is negligible and the increased pressure rise at 1 sec comes mostly from the steam separator external volume. The reason for this is as follows: After 0.3 sec in the steam separator external volume the pressure increase leads to an increase in the steam temperature in the "vapor" region, but because of the non-equilibrium model the energy transfer between the "vapor" region and the "liquid" region is reduced so maintaining the superheated steam in the "vapor" and dryer regions. In the steam separator region, however, there is a transfer of vapor from the liquid region at the level interface, because of the rising bubbles through the liquid region, and relative to this the reduction of the energy transfer across the interface due to the non-equilibrium model gives only a small effect.

3.3 "5-EQUATION" MODEL

Using the RETRAN-3D "constrained nonequilibrium" or "5-equation" model in the steam separator and steam separator external control volumes also reduces the heat transfer between the gas and the liquid phase. Thus the pressure at about 1 sec in the steam dome is increased (Figure 1 b). This increase however is much smaller than for the two-region non-equilibrium case. The reason for this is that the 5-equation model when used in conjunction with the bubble rise model, influences only the heat transfer within the regions above and below the liquid level and does not consider the heat transfer between the regions ie across the liquid level interface. The smaller pressure rise of the 5-equation model is also in line with the properties of the different models. While the homogeneous equilibrium model for the two-phase mixture considered constrains all phasic temperatures to the saturation temperature at the respective pressure, the 5-equation model constrains the vapor phase to the saturation temperature and permits the liquid temperature to float freely, and it is clear that, since there is no mechanism for subcooling the liquid in CV1 and CV4 (Figure 2) a major impact on the pressure increase through the use of this model is not to be expected.

4. NEW VERSION OF RETRAN-3D

The calculations presented above were performed using RETRAN-3D MOD003.0 [2]. Recently RETRAN-3D has been updated to MOD003.1 [7] thereby correcting the area change pressure drop for the case of multiple junctions. We consider now the influence of this up-date by example of the calculation with the two-region non-equilibrium model. Figure 3a shows that the calculations for MOD003.0 and MOD003.1 are nearly identical.

It should be noted that the combination of the two-region non-equilibrium model with the 5-equation model in the same control volume is currently not available for either code version, and the 4-equation model is always used in the code in combination with the two-region non-equilibrium model. Therefore calculations using the 4-equation and 5-equation option in the steam separator and steam separator external volumes, together with the two-region non-equilibrium model, always produce the same results (Figure 3a). Such a combination, allowing non-equilibrium between the liquid and the vapor region in combination with non-equilibrium between the liquid and the vapor phase in the liquid region would usefully extend the modeling capabilities of the code.

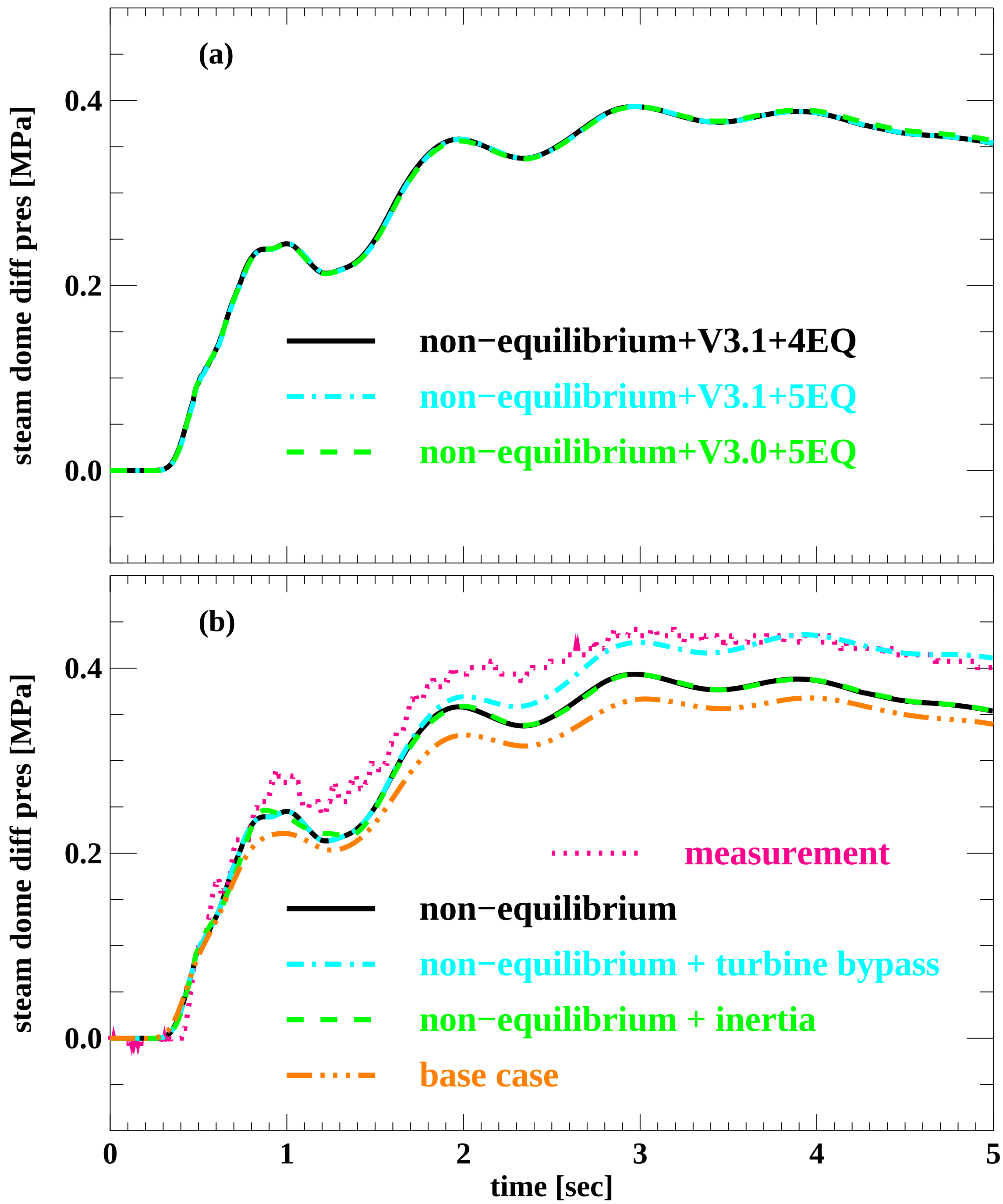

Figure 3: Steam dome differential pressure versus time - the two-region non-equilibrium model and variations.

5. THE NON-EQUILIBRIUM MODEL AND PARAMETER VARIATIONS

In the previous sections we saw that the two-region non-equilibrium model gives an improved agreement with the measured pressure in the steam dome. We have also seen that the agreement at later times can be improved by increasing the pressure losses in the turbine bypass line (Figure 1b). Now when the change in the bypass line is combined with the two-region non-equilibrium model in the steam separator regions the calculated pressure after 3 sec is in excellent agreement with the measured one, while there are still differences between 1 and 3 sec (Figure 3b). Moreover, as described above the change in the bypass line has almost no effect on the differential pressure in the steam dome for times up to 2 sec.

Finally we investigated a further feature of the steam separator region, ie that of the steam separator fluid inertia. Because of the complex flow behavior in the steam separator volume, ie flow in a vortex, there is not a unique value of the inertia, which is appropriate for all conditions and transients. To analyze the sensitivity on the fluid inertia, we approximately doubled the value in the steam separator inlet and more than doubled the value in the steam separator exit to the lower dryer (Figure 2). We chose these values from comparing an early analysis [4] of this transient with recent discussions [April 2002] in the e-mail forum of the benchmark. The effects of these changes on the steam dome differential pressure are relatively small (Figure 3b) for the case considered here, ie with pre-defined power. Note however, that the largest effect (~0.02 MPa) is for early times, and in particular before the time of the power peak (Figure 4), which is likely to influence the coupling of the thermal hydraulics to the core neutronics, which are not considered here. In fact, first calculations with 3D neutronics show that the effect of changing the inertia has a significant impact on the power evolution showing that the additional coupling of the core can promote the importance of system parameters.

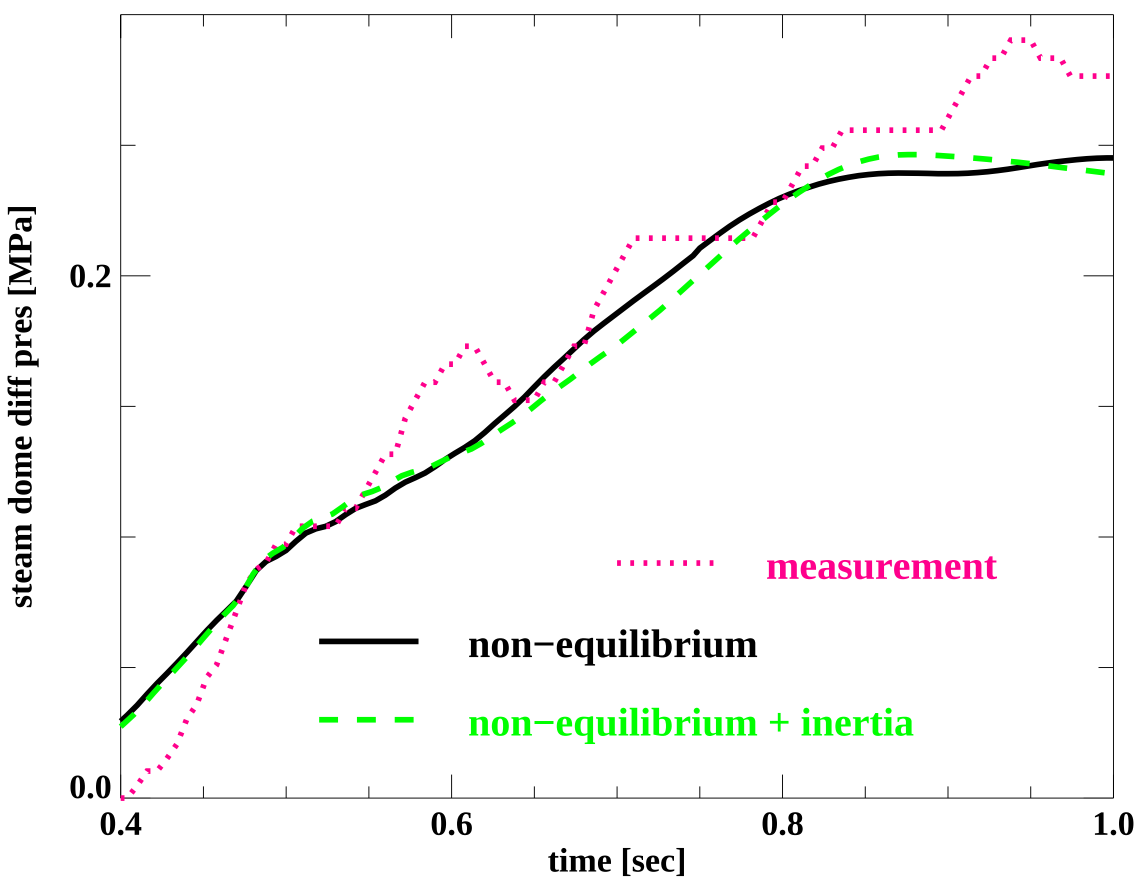

Figure 4: Steam dome differential pressure – the effect at early times of changing the inertia.

6. CONCLUSIONS

The results of the RETRAN-3D calculations for exercise 1 of the Peach Bottom 2 Turbine Trip 2, presented here gives good agreement with the measured data and in particular the steam dome pressure. In this paper we show that the modeling of the steam separator/downcomer region is crucial to correctly represent the pressure increase during the first 2 sec. Changes in the turbine bypass line also influence the pressure, however only after the first 2 sec. In order to demonstrate the importance of the modeling of the steam separator region and to highlight the important physical processes we have analyzed and compared the effects of re-nodalizing this region, of using the 4-equation and the 5-equation models, of using a two-region non-equilibrium model, and changing the fluid inertia, with the following results. For exercise 1, in which the experimental power is used as a boundary condition, the calculation in which the steam separator/downcomer region is re-nodalized, and when a two-region non-equilibrium model is used, provide the closest prediction to the measured system parameters expressed in terms of the steam dome pressure. These results then help to show that one of the important mechanisms that control the magnitude of the pressure rise at about 1 sec is the thermal disequilibrium in the separator and dryer region. Using the 5-equation model or changing the inertia in the steam separator region shows a smaller effect. We have also shown that the most recent code version RETRAN-3D MOD003.1 gives results very close to those from the previous version.

ACKNOWLEDGEMENTS

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