TEMPORAL ADAPTIVE ALGORITHM FOR SYNCHRONIZATION AND OPTIMIZATION OF THE PERFORMANCE OF MULTI-LEVEL COUPLED CALCULATIONS

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ABSTRACT

A temporal adaptive algorithm was developed to perform the synchronization and optimization of the performance of TRAC-BF1/NEM/COBRA-TF three-dimensional neutron/thermal-hydraulics subchannel analysis coupled code system. The multi-level coupling scheme for time synchronization of the TRAC-BF1/NEM and COBRA-TF under PVM is developed considering the different time-step selection algorithms of TRAC-BF1, NEM and COBRA-TF codes. The developed methodology allows one to synchronize the codes in time without doing significant code modifications to the time-step selection logic of the involved codes. The advantage of this approach is that COBRA-TF can capture the time-dependent nature of a given transient, without losing any time-dependent data. Results for steady state and transient calculations that show how the implemented temporal adaptive algorithm works are presented. In addition selected results are presented to illustrate dynamic behavior and the type of thermal-hydraulic boundary conditions provided by the system code.

1. INTRODUCTION

TRAC-BF1 and NEM are coupled by using parallel virtual machine (PVM) environment (Geist, 1994). The numerical scheme of the PVM coupling is a semi-implicit scheme for the calculated power (Lu, 1997). In most cases (especially during steady state calculation), the number of times the three-dimensional (3-D) kinetics calculations performed can be optimized to speedup the calculation. For this purpose, a multiple time step marching scheme is implemented in TRAC-BF1/NEM calculation. This scheme allows TRAC-BF1 solution to march several steps while NEM only marched one large time step. For the coupled TRAC-BF1/NEM code a 3-D kinetics variable time step algorithm has been developed and implemented together with a meshing scheme with the thermal-hydraulic time step algorithm. The kinetics algorithm has an automatic time step control procedure that monitors the temporal truncation errors (global –power and local – neutron flux) during a given time and adjusts the time size automatically. For any successive time integration step, it is required that the maximum scaled truncation error be smaller than a user-specified error tolerance ε (ε_G – global, set up to limit global power change to 1% per time step and ε_L – local, set up to limit local flux change to 10% per time step). The global and local relative errors are calculated by evaluating the first derivative in time of the monitored variables (power and flux). The rate of accumulation of the global error ($d\varepsilon_G/dt$) is calculated in the L_2 norm while the rate of accumulation of local error is calculated in an L_1 norm. The required kinetics time step size is determined as follows:

$$T_G^K = \frac{\varepsilon_G}{\frac{d\varepsilon_G}{dt}} \tag{1}$$

$$T_L^K = \frac{\varepsilon_L}{\frac{d\varepsilon_L}{dt}} \tag{2}$$

$$T_{estimate}^K = \min(T_G^K, T_L^K) \geq T_{min}^K \tag{3}$$

T_{min}^K – equal to the thermal-hydraulic time step size

$$T_{final}^K = \min(T_{estimate}^K, T_{max}^K) \tag{4}$$

T_{max}^K – specified by the user

In order to provide best-estimate analysis of local safety parameters, the COBRA-TF thermal-hydraulics sub-channel analysis code (Solís, 2000) is coupled to the TRAC-BF1/NEM code using also PVM. Since TRAC-BF1/NEM and COBRA-TF codes use their own algorithm to select the time-step size during a given calculation, some techniques have to be implemented in order to have a good synchronization of the codes when marching on the same time scale. COBRA-T has more restrictive convergence criteria as compared to the system TRAC-BF1 code. There is a single input parameter in COBRA-TF, which could be used for relaxing the time-step size. This parameter is the so-called outer iteration convergence criterion. Suggested value of 0.001 is given in the COBRA-TF User's Manual (Paik, 1985). The other parameters used for iteration control are the maximum number of outer iterations and the maximum number of vessel iterations. Table 1 shows a comparison of the iteration control parameters between the two codes. Table 2 shows a comparison of the relevant thermal-hydraulic parameters evaluated during the time-step calculation. There are in the COBRA-TF time-step selection algorithm two other parameters that are also checked out during the calculation of a new prospective time-step size. These are the Courant limit and the vessel error limit. These two parameters combined with pressure and void fraction are used to come up with the total error limit. Since COBRA-TF has been designed as a transient code, it does not have a convergence criterion for steady state calculation. The selected approach is based on the principle that the coupled synchronization and optimization has to be achieved without affecting the time-step selection logic of the coupled codes. This approach is presented in detail in the next section.

Table 1 Iteration control

TRAC-BF1	COBRA-TF
Convergence Criterion for outer iteration	Convergence criterion for outer iteration
Convergence criterion for vessel iteration	Not available
Convergence criterion for steady state	Not available
Maximum number of outer iterations	Maximum number of outer iterations
Maximum number of vessel iterations	Maximum number of vessel iterations

Table 2 Thermal-Hydraulic parameters evaluated during time-step calculation

TRAC-BF1	COBRA-TF
Pressure	Pressure
Void Fraction	Void fraction
Liquid Velocity	Not available
Vapor Velocity	Not available
Liquid Temp	Not available
Vapor Temp	Not available
System Metal Temp	Not available
Rod Temp	Not available

2. TRAC-BF1/NEM/PVM/COBRA-TF Synchronization in Time

The approach used for synchronizing the codes is illustrated in Figure 1. This figure shows that a hot-channel analysis option is added as a second level coupling in the PVM environment to the normal TRAC-BF1/NEM calculation scheme (first level coupling). The hot-channel calculation is started by the NEM code under the PVM environment. The transfer of data among the codes is performed using the PVM data transfer capabilities. The TRAC-BF1/NEM code sends *timepvm* to COBRA-TF, which is the time-step just selected for a given neutronic/thermal-hydraulic calculation. The number of TRAC-BF1/NEM time-step calculations before spawning COBRA-TF is left to the user's criteria. Typically two time-steps is an acceptable choice. For the case of a transient calculation, not much change (if any) will be "missed" by COBRA-TF, since at the beginning of the transient calculation; TRAC-BF1/NEM time-step size is usually very small. This very short initialization time should be enough, assuming that an acceptable steady state calculation was achieved during the TRAC-BF1/NEM initialization step. The TRAC-BF1/NEM multiple time step marching scheme is shown in Figure 2. This figure also shows how COBRA-TF is marching in time. Figure 3 shows the coupled code where a one-to-one time step calculation is performed by TRAC-BF1 and NEM. The COBRA-TF calculation sequence is shown as well.

In summary, the synchronization algorithm proceeds as follows. TRAC-BF1/NEM is started first under PVM environment. After some time-steps in the calculation, COBRA-TF code is initialized. The above procedure will allow one to have all the hot-channel parameters (thermal-hydraulic boundary conditions, pin power reconstruction, and etc.) available to initialize the hot-channel analysis code. At this step, COBRA-TF has started under PVM environment and some of the input data are replaced with data coming through PVM. Most important, some of the time-step cards given as input are replaced during this initialization. The end of the time domain given is the time-step size sent by TRAC-BF1/NEM (the problem calculation time is accumulated using this time step). In other words, the system code takes control of COBRA-TF time-step cards. Typically, it will take several COBRA-TF time steps to complete the calculation of a single TRAC-BF1/NEM time-step. It depends on the dynamic of the transient. At some point, the time-step size of both code, almost matches each other.

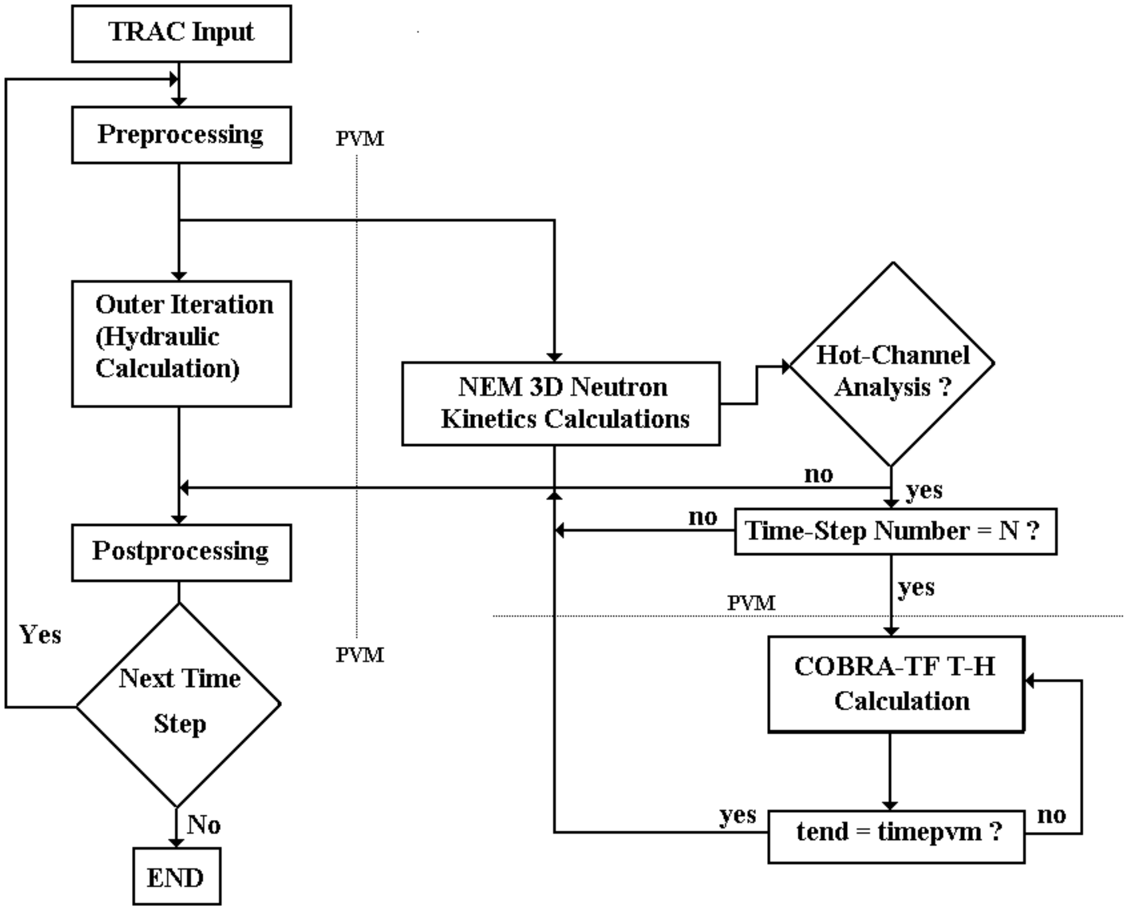

Fig. 1 TRAC-BF1/NEM/PVM/COBRA-TF Time Synchronization Approach

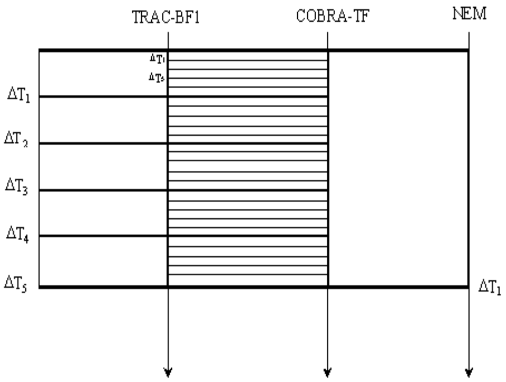

Fig. 2 Multiple time step algorithm

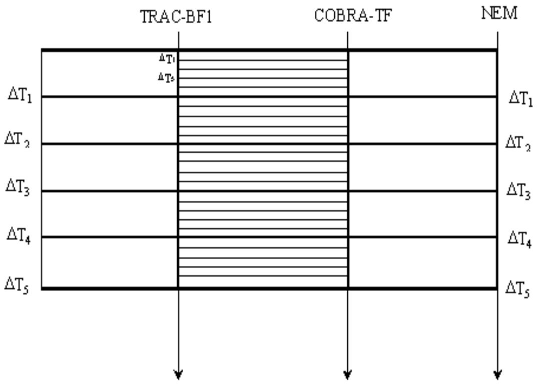

Fig. 3 Base coupling scheme

2.1 Steady State Case

An example of the time synchronization achieved for the coupled codes is presented in Figures 4, and 5 for a steady state calculation. Figure 4 shows the results from zero to five hundred time-steps. It can be seen in this figure that at the beginning of the calculation, COBRA-TF takes a number of calculations to reach the coupled code calculation time. As the calculation proceeds, thermal-hydraulic distribution begins to reach more stable values, as it can be seen in Figure 5 from 500 to 1000 time steps. At this point, the number of time-steps taken by COBRA-TF to complete a coupled code time-step decreases making a more tight synchronization in time between the codes. For illustration purposes, a comparison between COBRA-TF time step sizes vs. TRAC-BF1/NEM is presented in Figure 6. It can be seen in this figure that TRAC-BF1 reaches a point where the time-step size remains constant for the rest of the calculation. On the other hand, COBRA-TF time-step size is continuously varying.

Since the COBRA-TF code was designed as a transient subchannel analysis code, coupling with the system code is more challenging for steady state calculations. In reality, during steady-state calculation, COBRA-TF is performing a “null” transient (quasi steady state calculation) rather than a steady-state one. After achieving convergence of the coupled code for the steady state case, dump and restart options are activated for performing further the transient analysis.

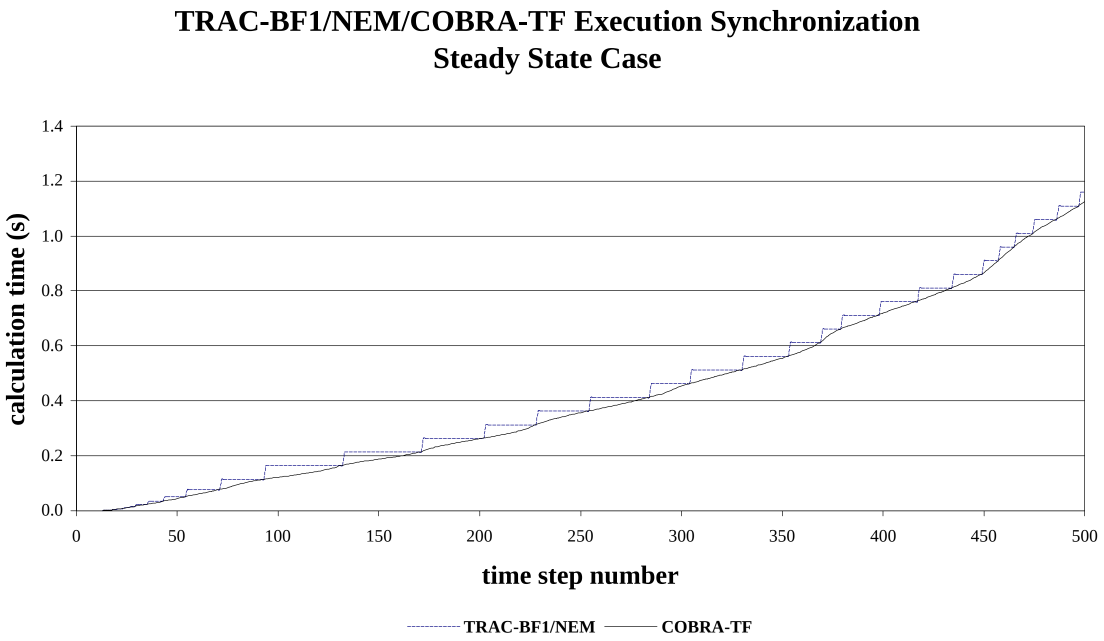

Fig. 4 Steady State Calculation From 0 to 500 Time-Steps

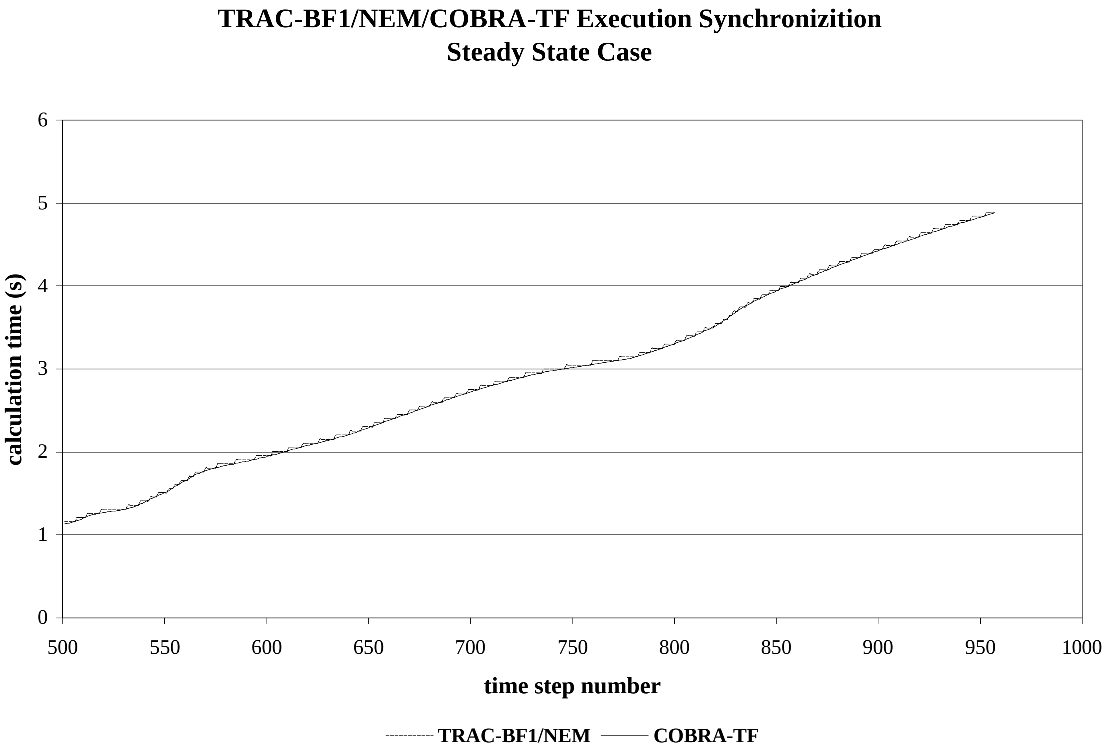

Fig. 5 Steady State Calculation from 500 to 1000 Time-Steps

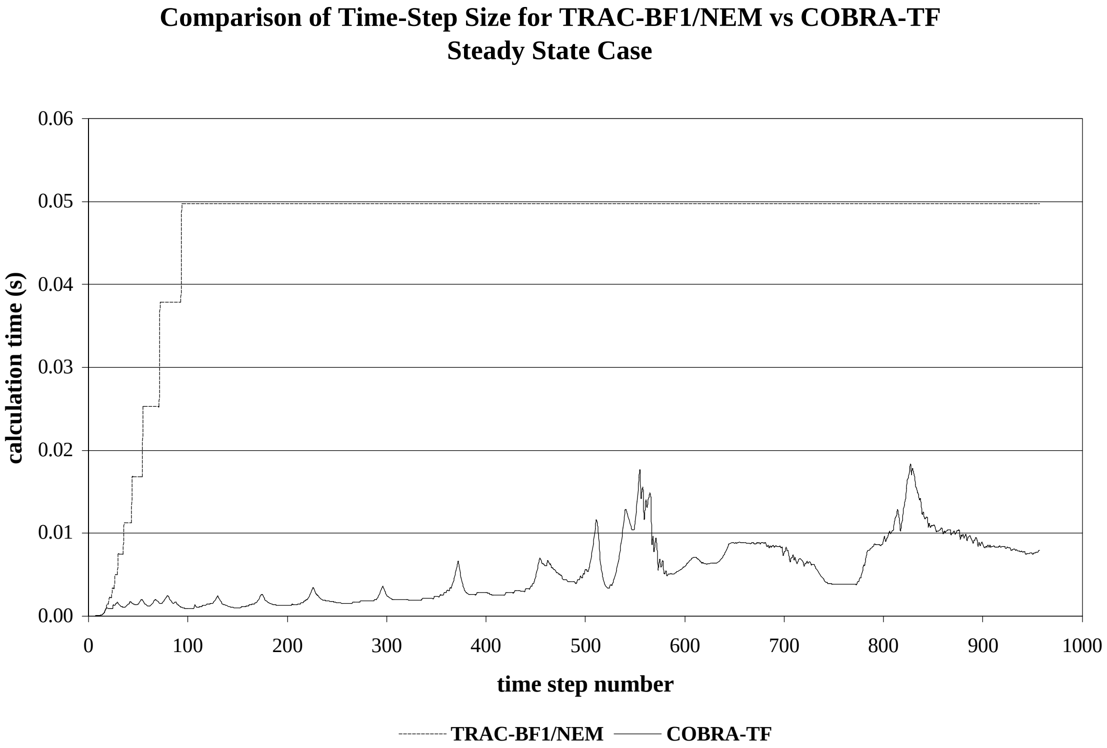

Fig. 6 Time-Step Size Comparison for Steady State Calculation

2.2 Transient Case

Results of a transient calculation are shown in Figure 7 through Figure 11. Figure 7 shows the calculation from 500 time-steps to 1500. It can be seen here, that in the last part of the transient, COBRA-TF time-step size increases, therefore taking a less number to complete a system code time-step. Figure 8, shows the range from 1 time-step to 500. The little horizontal lines shown here are the TRAC-BF1/NEM time-steps, which is kept constant during a COBRA-TF calculation.

Since the example transient is very mild in terms of dynamic response, there is just a small difference between the number of time-steps during steady state and transient calculation. This is shown in Figure 9, where it can be seen that at the beginning of the calculations, the time-step sizes match for steady state and transient calculation. Figure 10 compares the time-step step size for COBRA-TF quasi steady state and transient calculation. Figure 11 shows a comparison of the time-step size between the codes. COBRA-TF time step size is always smaller than the time-step taken by the system code.

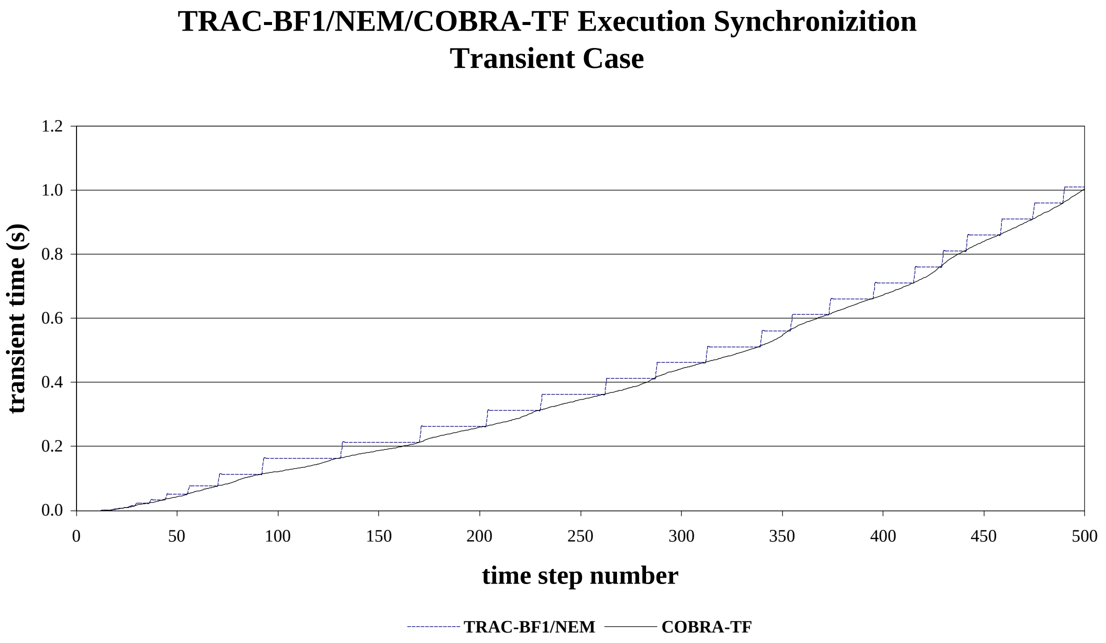

Fig. 7 Transient Calculation From 0 to 500 Time-Steps

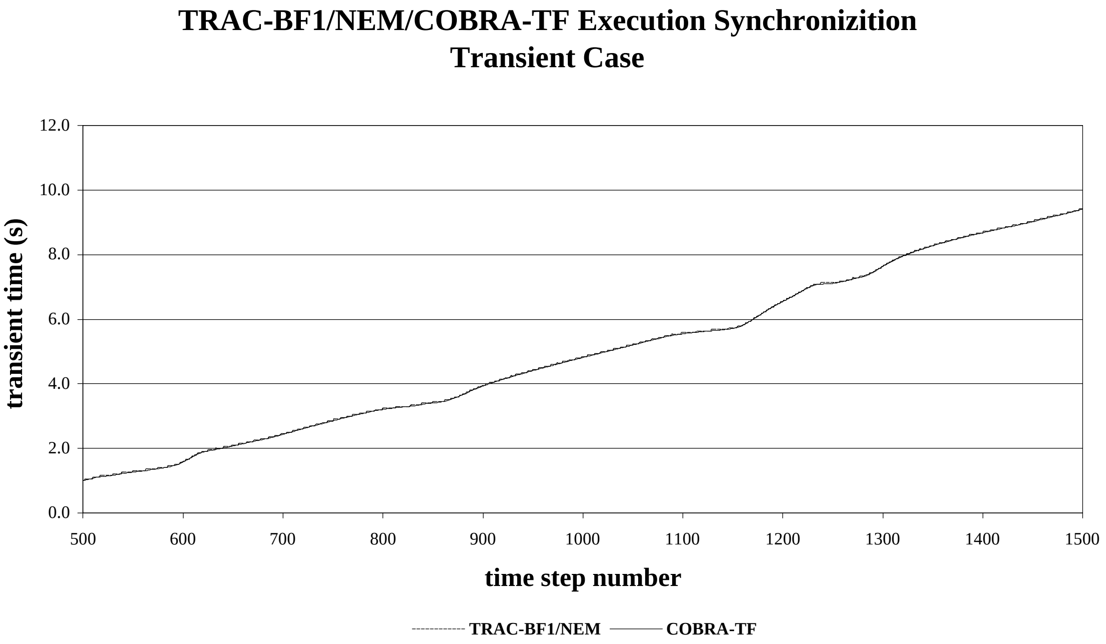

Fig. 8 Transient Calculation From 500 to 1500 Time-Steps

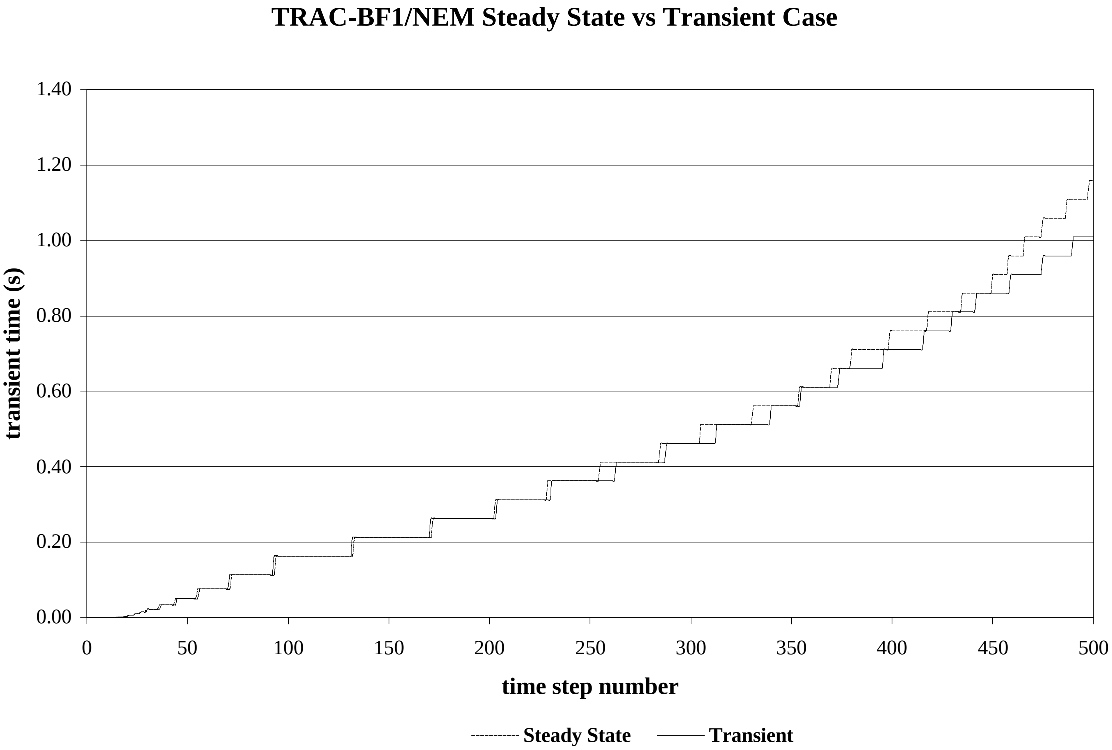

Fig. 9 Comparison of Steady State vs. Transient Case

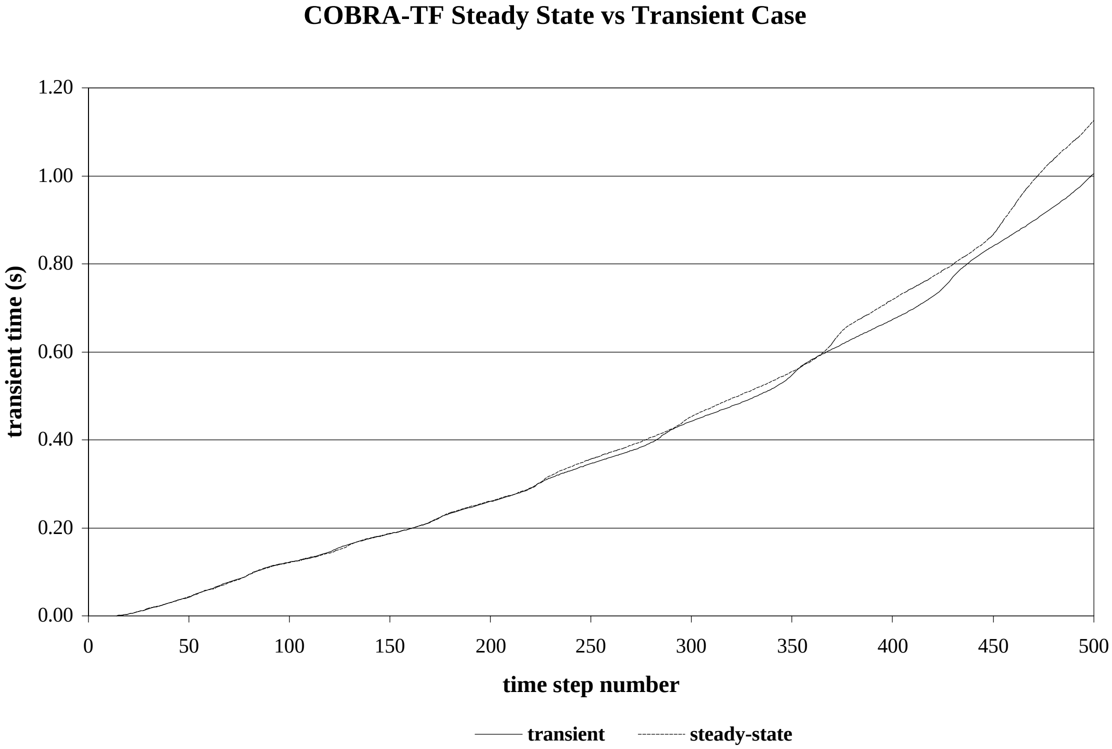

Fig. 10 COBRA-TF Steady State vs. Transient Case

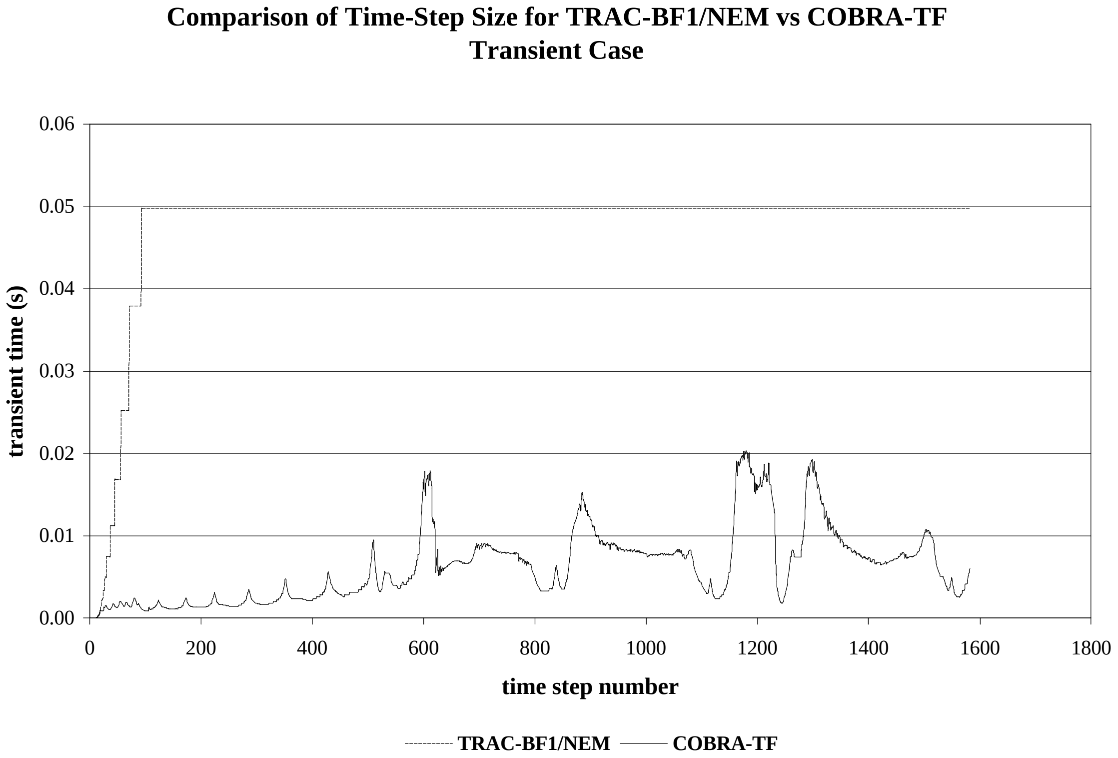

Fig. 11 Comparison of Time-Step Size (Transient Case)

3. Dynamic Response Testing of the Refined Hot-Channel Analysis Module

The stand-alone version of COBRA-TF thermal-hydraulic hot channel analysis code accounts for transient response through the use of forcing functions. There are a number of these forcing functions that can be implemented for a given calculation. For instance, at the start of a transient simulation, fixed axial power profile tables are given as part of the thermal-hydraulic hot channel analysis calculation. At some point in the transient, the power forcing functions are activated and the initial power profile is modified according to the value of the power function factor specified in the input data. The disadvantage of this procedure is that the user should know in advance exactly where on time power is going to vary, and how much the magnitude of this variation is going to be. This approach may be used for design purposes, but it does not really reproduces the actual dynamic behavior.

Coupling the hot-channel analysis code with the TRAC-BF1/NEM code under PVM environment removes the need of having power forcing functions tables at the start of a given calculation. Power profiles of the modeled fuel rods are provided on-line through the use of the pin power reconstruction of the NEM code. For the case of thermal-hydraulic boundary conditions, forcing functions can also be specified to represent the transient simulation. In some cases, it is possible that the thermal-hydraulic boundary conditions do not vary too much during a given calculation. The new multi-level coupling capability captured well this variation in a best-estimate manner by making use of the available thermal-hydraulic information coming from the system code. This information is passed through PVM for each time step. Further in the framework of this time step the transient simulation of the subchannel calculation is left to the COBRA-TF thermal-hydraulic capabilities.

For testing purposes, the dynamic response of the thermal-hydraulic boundary conditions is given in Figures 12 through 16. These results correspond to a BWR control rod drop simulation. Figure 12 shows the channel inlet enthalpy, which basically remains constant during the transient calculation, except for a small variation that is caused by the total reactor thermal power rise. Since, the core flow is very small (approximately corresponding to natural circulation conditions), it takes some time until the power rise is felt at the reactor lower plenum and then at the core inlet. Figure 13 shows the channel outlet enthalpy - the heat up of the coolant causes a large change comparing to the initial value. Figures 14 and 15 show the channel inlet and outlet pressure respectively. Little change is noticed as compared to the channel inlet enthalpy. Figure 16 shows the channel inlet mass flow rate where also some variation is noticed, especially during the big power rise. In general, the expected dynamic variation is going to depend on the dynamics of the transient being simulated. With the above example, the dynamic capability of the boundary conditions is demonstrated and tested. For more involved system transients these changes will be more significant. It will be very difficult to model these changes with the stand-alone COBRA-TF code using forcing functions. In addition, the transient behavior should be known in advance. The multi-level coupled TRAC-BF1/NEM/COBRA-TF code system provides on-line best-estimate transient simulation on both global and local levels.

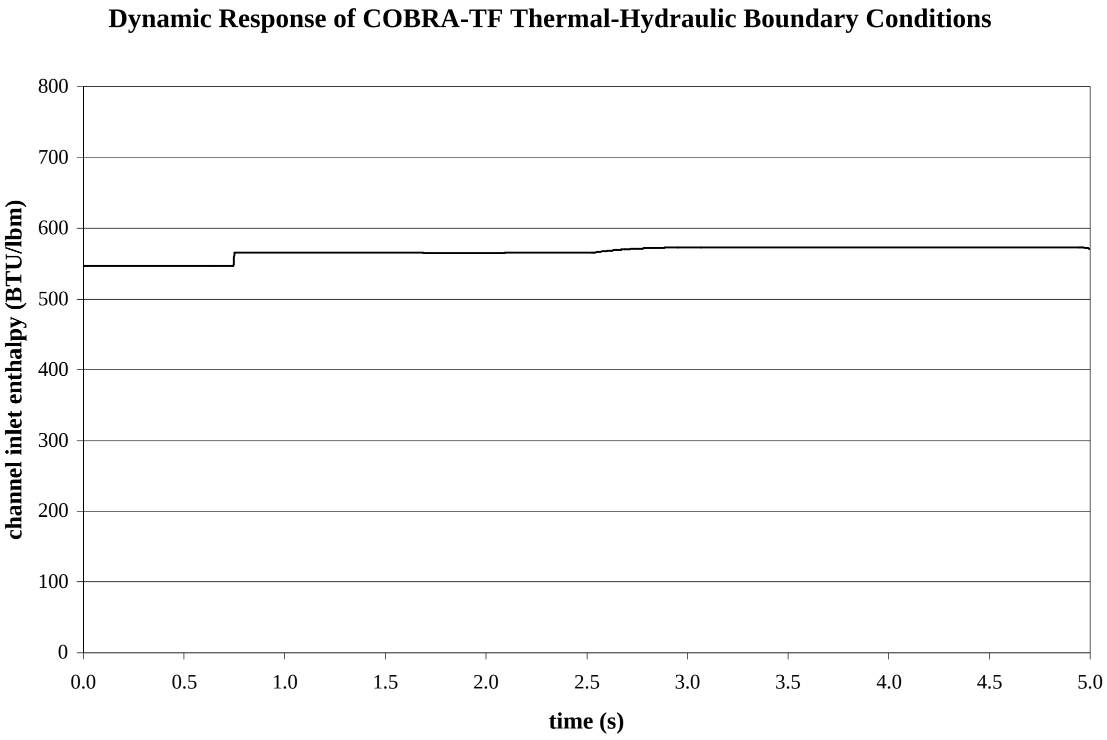
Dynamic Response of COBRA-TF Thermal-Hydraulic Boundary Conditions

Fig. 12 Hot channel inlet enthalpy

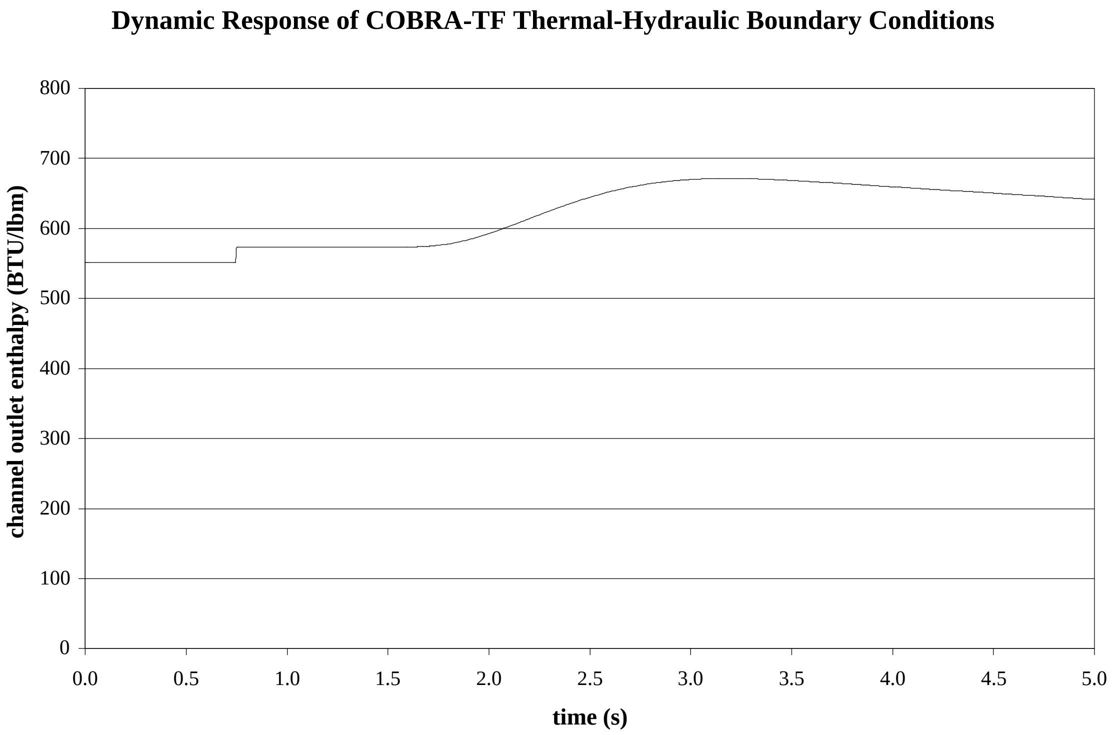
Dynamic Response of COBRA-TF Thermal-Hydraulic Boundary Conditions

Fig. 13 Hot channel outlet enthalpy

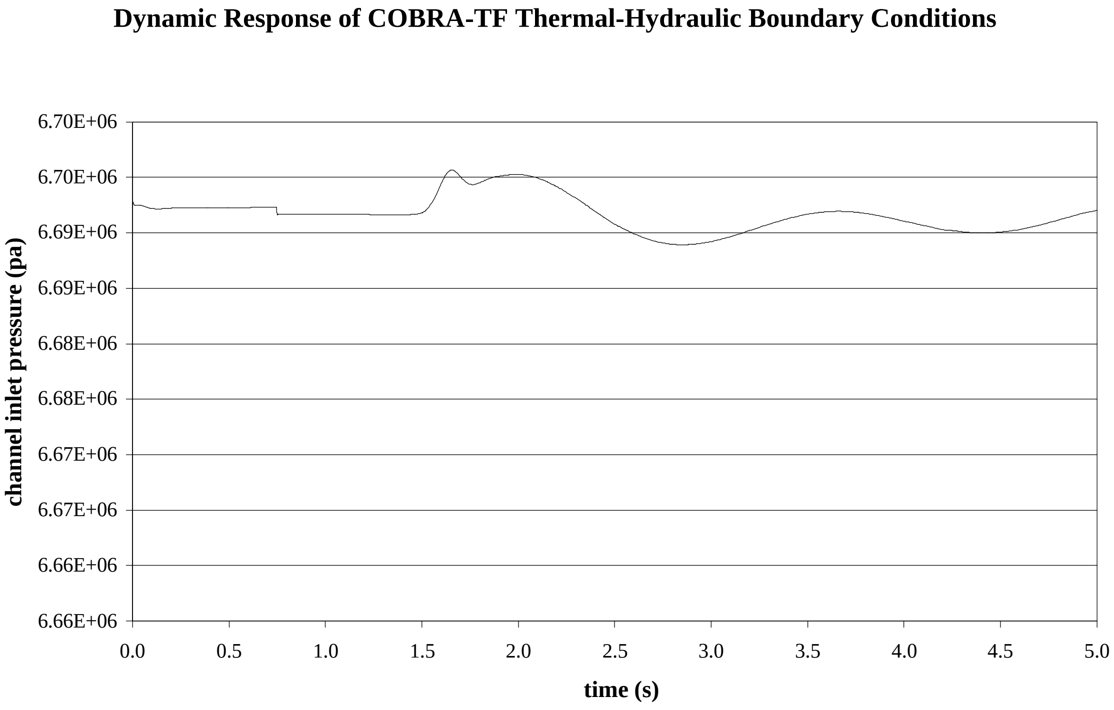
Dynamic Response of COBRA-TF Thermal-Hydraulic Boundary Conditions

Fig. 14 Hot channel inlet pressure

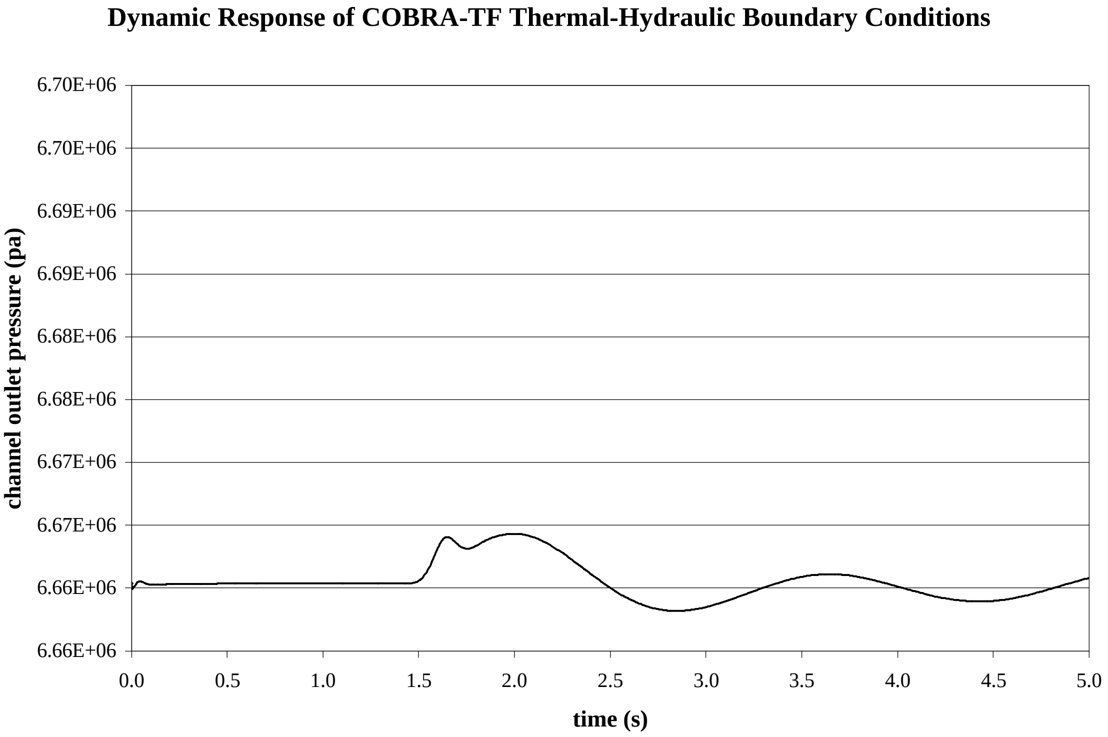

Fig. 15 Hot channel outlet pressure

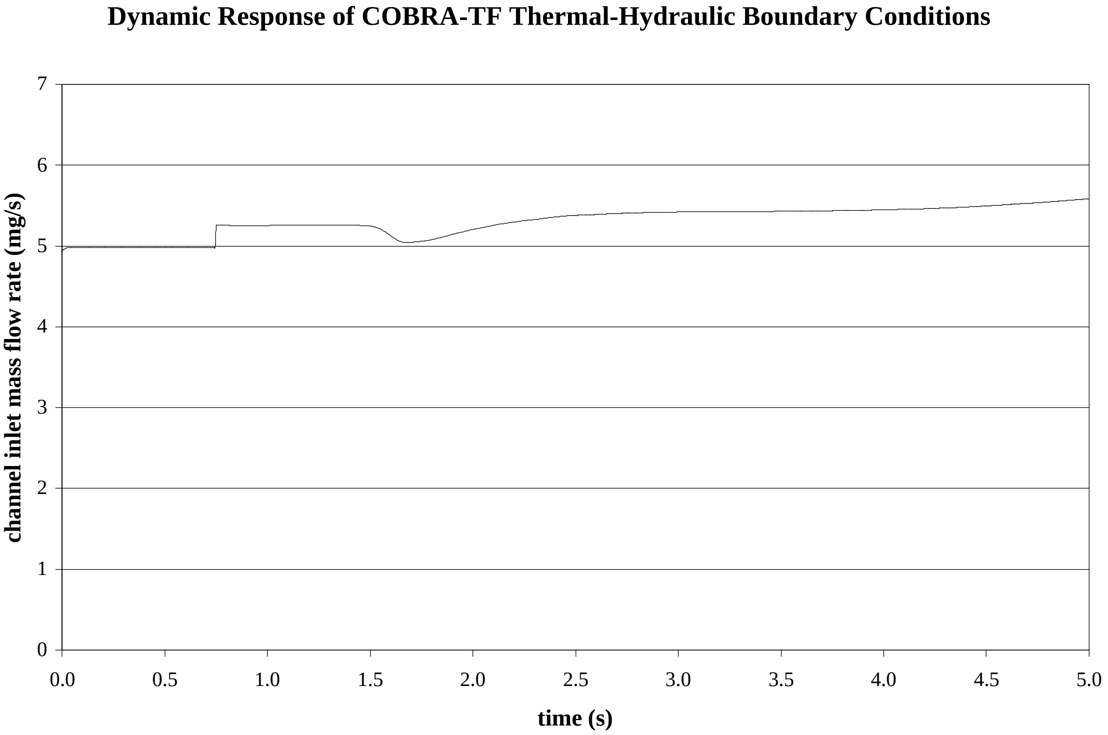

Fig. 16 Hot channel mass flow rate

CONCLUSIONS

The temporal adaptive algorithm for time synchronization of the TRAC-BF1/NEM and COBRA-TF under PVM is designed taking into account the different time-step selection algorithms of both codes. This approach allows one to synchronize the codes in time without doing significant code modifications to the time-step selection logic of both codes. The advantage of this approach is that COBRA-TF can capture the time-dependent nature of a given transient without losing any time-dependent data. One shortcoming is that since COBRA-TF time-step is usually smaller, the computation time increases for mild transients where the time-step size of the system code increases. An optimization procedure is being developed directed to enhance the current algorithm for such cases. For very rapid transients, this shortcoming is not important, since the time-step size of both codes is very similar in size. The new capability can be used for performing a subchannel analysis that better reflects the dynamic nature of the boundary conditions imposed to the subchannel model. The time-dependent nature of the boundary conditions was demonstrated when performing a transient simulation using the TRAC-BF1/NEM system code and the subchannel analysis code COBRA-TF coupled through the use of PVM environment.

NOMENCLATURE

L_1	norm
L_2	norm
T	time
ε	error

Subscripts

G	global
L	local
max	maximum
min	minimum

Superscripts

K	time step number

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