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Thermal-Hydraulic Simulation of a Radiant Steam Boiler Tube Rupture Transient Using Relap5/Mod3.2

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Abstract: A steam boiler is a complex system comprised of numerous components. In the operation of industrial steam boiler, it is very important to evaluate different accident scenarios in actual plant conditions. One of the main accidents is steam generator tube rupture. Numerical simulation using best estimate computer codes like Relap5 are useful for understanding thermal-hydraulic behavior of a steam boiler during normal and accidental operating conditions. In this study, the analytical investigation of an industrial steam boiler behavior during feedwater line break accident is discussed. A detailed nodalization of the steam boiler installation is developed based on Relap5/Mod3.2 to be suitable for the analysis of the various accidents. The control and regulation systems are also considered. Water level, pressure, temperature and flow rates profiles are presented in various steam boiler system components. From the result, the thermal-hydraulic code correctly predicts the behavior of the main plant parameters in comparison with the experimental data and how the control system when required can successfully mitigate the accident.

Key words: Natural circulation steam boiler, Relap5/Mod3.2 code system, steady-state simulation, transient simulation, tube rupture accident, Algeria

INTRODUCTION

The use of large boilers for steam generation is quite common in industry; they received considerable attention from industry and academia since, they frequently account for an important part of the overall fuel consumed in a plant (Adam and Marchetti, 1999). Now-a-days, steam boilers with natural circulation have a wide range of applications such as power cycles and industrial heating processes due their advantageous features (Waletr and Linzer, 2006). However such facilities are subjected to several operating failures that could expose the system structural integrity to serious hazard and huge economic and human life losses (Rahmani *et al.*, 2009). A common steam boiler fault is the tube leak in the riser and downcomer sections due to aging and thermal stress. Early detection of such faults in operation are important; it help in reducing possible damage to equipments and productivity loss caused by (otherwise) unscheduled boiler shut down; it also ensures safety for operators (Sun *et al.*, 2002).

Several numerical and experimental investigations have been performed to understand the thermal-hydraulic characteristics in conventional steam boiler. In the past, traditional methods relied heavily on expensive experimentation and the building scaled models but now-a-days, a more flexible and coast effective approach is available through greater use of mathematical modeling and computer simulation. The recent advances in the computer technology have made it possible to perform complex calculations efficiently and even faster than real time. The best estimate system codes like Relap5 are extensively used in the area of design and safety evaluation of thermal-hydraulic systems. In comparison with experimental and analytical methods, numerical simulations are also efficient tools for safety and integrity assessment (Damir, 2000).

The purpose of this research is to develop a Thermal-hydraulic Model of an industrial steam boiler to analysis the boiler tube rupture accident using Relap5/Mod3.2 computer code. The studied steam boiler is a radiant type, natural circulation, one drum and a combustion chamber in pressure. The steam boiler is installed in a typical complex of natural gas liquefaction. The steam boiler is designed to produce 374 ton h^{-1} of superheated steam at 73 bars and 487°C (Deghal *et al.*, 2011).

In this research, the variation of thermal-hydraulics parameters in a steam boiler facility under tube rupture accident at a radiant steam boiler is analyzed by Relap5/Mod3.2 thermal-hydraulic code. The results obtained by this code are compared with the experimental power plant data. The simulation of this accident, it was

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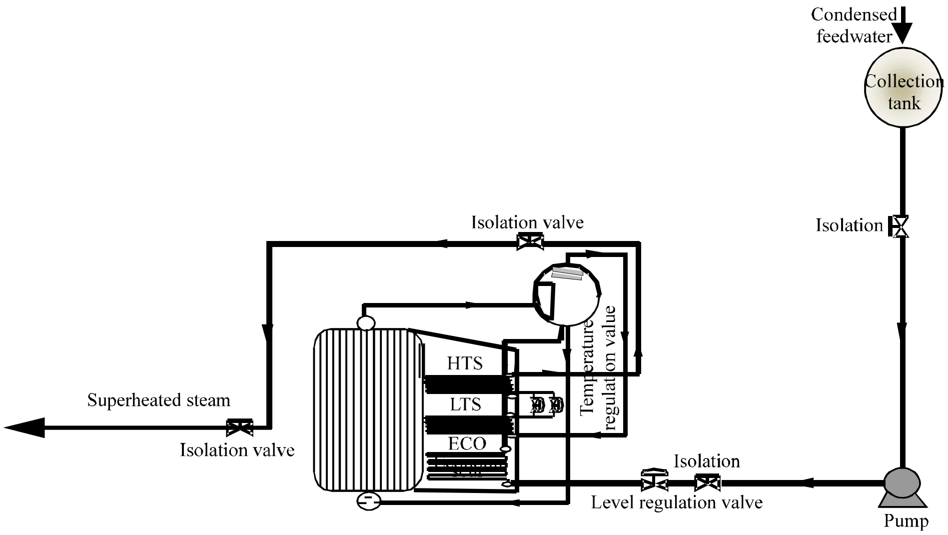

Fig. 1: Schematic representation of the steam boiler installation

supposed that after the establishment of a steady-state condition in the system, tube water leakage is a result of an instantaneous break happened with equivalent diameter of 80 mm situated at the feedwater line from economizer to steam drum.

Steam boiler description: The industrial steam boiler, an ABB ALSTOM type is installed in the complex of natural gas liquefaction; generates a nominal steam capacity of 374 tons h^{-1} at superheated steam conditions of 73 bars and 487°C (Deghal and Chaker, 2008). It is composed of 3 main parts; the main feedwater line, the steam generator and the main superheated steam line. Figure 1 shows a schematic representation of the facility. The steam boiler is designed to be operated by combination of a manual and automatic operation. Several operations such as startup and shutdown are operated manually. Once the major thermal-hydraulic parameters reach the desired steady-state condition they are switched aver to be controlled automatically by feedback control logics to maintain the achieved steady-state.

The integrated control and monitoring systems includes various safety systems designed to prevent postulated damage during normal and abnormal transients. The top of the steam drum is equipped with three safety valves that control system pressure. Two other safety valves are installed on the main superheated steam line and there are four isolation valves and four flapper valves in different locations of the steam boiler facility. The rear pass receives two superheaters and tree economizers. The drum constitutes a necessary water reserve for the riser from what it receives the mixture of steam/water. Feedwater flows into the lower part of the drum according to the water quantity needed. Water in the drum flows into five downcomers and then flows through tubes in a riser (evaporating tubes) which are fabricated as membrane walls and vertical tube bundles. Water circulates due to the density difference of water in legs the loop. The main operating parameters of the steam boiler are shown in Table 1.

Table 1: Operating characteristics of steam boiler

Technical parameters	Values
Steam flow rate (time h^{-1})	374.0
Drum pressure (bar)	79.6
Feedwater inlet temperature (°C)	118.0
Air flow rate (Nm^3 h^{-1})	344800.0
Natural gas flow rate (Nm^3 h^{-1})	45699.0
Air excess in the furnace (%)	1.3
Outlet furnace gas temperature (°C)	1147.0

Operating characteristics of steam boiler: In the combustion chamber, heat transfer is dominated by radiation while conduction and convection contribute to <5% of heat transfer (Dick, 2002). The thermal energy of the fuel gas exiting the furnace is transferred by convection to remainder of the steam boiler components (economizer tubes, superheater tubes).

MATERIALS AND METHODS

Relap5/Mod3.2 presentation: The Light Water Reactor (LWR) transient analysis code, Relap5 was developed at the Idaho National Engineering Laboratory (INEL) for the US Nuclear Regulatory Commission (NRC). Code uses include analysis required to support rulemaking, licensing audit calculation, evaluation of accident mitigation strategies, evaluation of operator guidelines and experiment planning analysis. Relap5 has also been used as the basic for a nuclear plant analyzer. Specific applications have included simulation of transients in LWR systems such as loss of coolant. Relap5 is a highly generic code that in addition to calculating the behavior of a reactor coolant system during a transient can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear system involving mixture of steam and water. The Relap5/Mod3.2 Hydro-dynamic Model is based on non-homogeneous, no equilibrium, six equations system for the two phases system that solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The general solution procedure is to subdivide the system into a number of control volumes connected by flow paths. The code includes many generic components models from which general systems can be simulated. The component models include pumps, valves, pipes, heat structures, reactor point kinetics, separators, control system components, etc. The conduction heat transfer model is one-dimensional using a staggered mesh to calculate temperatures and heat flux vectors (Borges *et al.*, 2000).

Steam boiler modeling: This section describes the modeling assumptions and nodalization for the development of a Relap5/Mod3.2 Model for radiant steam boiler (Deghal *et al.*, 2011). The Relap5 Model of the facility was developed for analyses of operational occurrences, abnormal events and design basis scenarios. Data and information for the modeling of these systems and components were obtained from the steam boiler documentation and from the power plant staff. The input model has been transformed into a Relap5 input deck which is composed of the following groups of data:control variable cards, trip and control system data, hydro-dynamic component data, heat structure data and general tables. The heat densities involved between the hot gases and the external tube surface are imposed by table entry. It is entered as the right boundary conditions to simulate the convective heat exchanger related to convective section as well as the radiation heat transfer in the furnace using the external heat exchange Surface (S), the heat flux densities are obtained according to the relation q = Q/S where, Q is the transferred heat estimate from the energy balance between the hot gases and the boiler exchangers (Deghal *et al.*, 2011).

The developed nodalisation includes 582 regular volumes, 571 junctions, 142 heat structures and 7 time dependent volumes. The nodalization diagram is shown in Fig. 2. The main feedwater line is modeled using component BRANCH 200 to modeled the collection tank, the centrifuge feedwater pumps are modeled by the PUMP component 151 and 152 and the pipe lines are modeled using the component PIPE 201 through 213. The feedwater is supplied by the condenser specified by time dependent volume 400. To simulate the drum water level control valve, researcher used the component servo-valve 011 and for the isolation valve, researcher utilized the motor-valve 003. The economizer is modeled using 41 volumes, 40 junctions and 20 heat structures (pipe 171). The main steam line includes; steam pipeline, the primary and secondary superheater, desuperheter temperature control system, isolation and safety valves. The pipeline is modeled by component PIPE 302 through 311 and the BRUNCH 083, 084, 085 and 086. The superheater SBT and SHT are modeled using 16 volumes, 15 junctions and 20 heat structures (pipe 176 and 180) for each one. The isolation valves are modeled by motor-valve 001 and 002. The steam temperature regulation valve is modeled with two servo-valves 012 and 013. The desuperheater pipeline

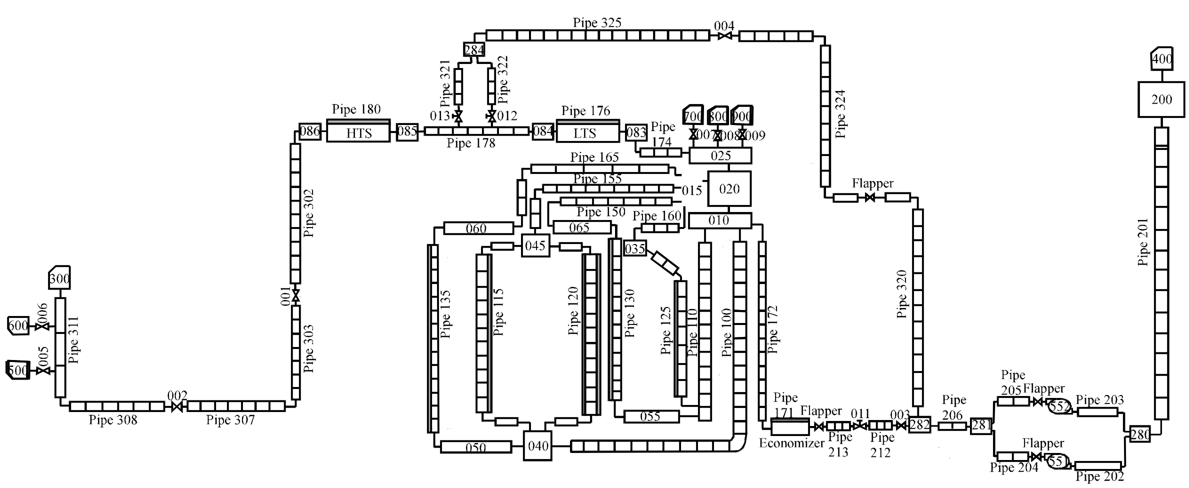

Fig. 2: Relap5/Mod3.2 nodalization diagram of the steam boiler

is modeled using the PIPE 320, 321, 322, 324 and 325. The safety valves are modeled using the trip-valve 006 and 005 connected to the time dependent volume 600 and 500, respectively. Time dependent volume 300 sets the boundary conditions of outlet superheated steam. The control system used in the steam boiler facility is composed of the water level regulation in the steam drum and the steam temperature regulation at the outlet of the superheater. The control system is modeled by Feedctl component to control the water level in the drum and Steamctl component to control the steam temperature. These controllers are Proportional Integral (PI).

Qualification: The validation of a Relap5 nodalisation aims to reproduce the measured steady-state conditions of the system with acceptable margins. The nodalisation may be considered qualified when it has a geometric fidelity with the system, it reproduces the measured steady-state condition of the system and it demonstrates satisfactory time evolution conditions (D'auria and Galassi, 1998). The qualification assessment of the model is shown. The model prediction was compared with the available experimental data under steady-state. As it can be shown in Table 2, the results for code are in good agreement in comparison with the steam boiler experimental data, in fact the regulation systems for the steam generator water level and the outlet superheated steam temperature enable to achieve a satisfactory steady-state. Thus, the comparison between the simulation results against plant data demonstrates clearly the ability of the model to predict correctly the thermal-hydraulic behavior of the radiant steam boiler. Figure 3

Table 2: Comparison between plant and calculated data at steady-state

Thermal-hydraulic parameters	Plant data	Relap5 data
Exit steam flow rate (time h^{-1})	374.00	374.357
Feedwater flow rate (time h^{-1})	374.00	374.121
Outlet steam temperature (°C)	292.00	292.368
Drum pressure (bar)	76.90	77.200
Vapor pressure (bar)	73.00	73.199
Feed water inlet temperature (°C)	118.00	119.500
Outlet economizer temperature (°C)	287.00	287.030
Inlet SBT superheater temperature (°C)	292.00	292.316
Outlet SBT superheater temperature (°C)	370.00	370.848
Inlet SHT superheater temperature (°C)	322.00	320.141
Outlet SHT superheater temperature (°C)	487.00	487.338
Pressure at collection tank (bar)	1.89	1.890
Outlet pump pressure (bar)	91.93	94.150
Inlet steam generator pressure (bar)	82.00	78.200
Drum water level (mm)	860.00	860.003

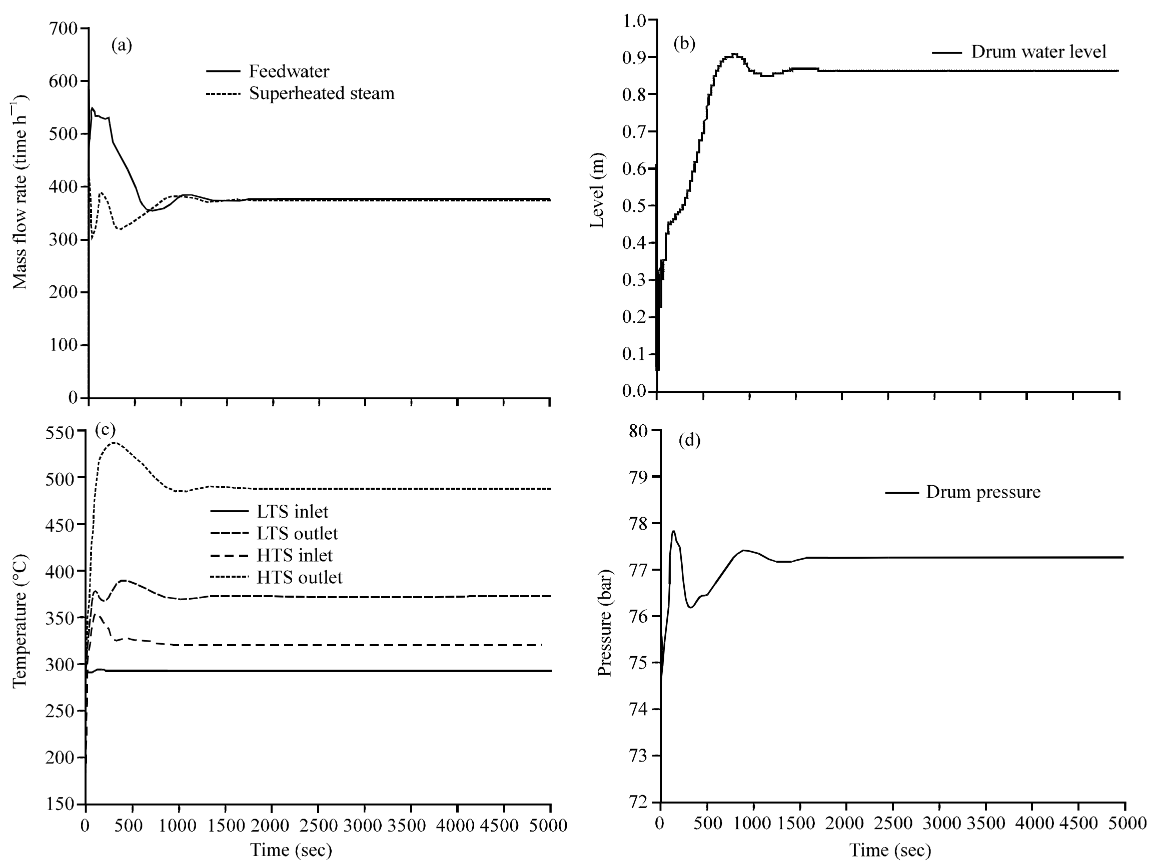

Fig. 3: Main thermal-hydraulic history plots during steady-state

shows the steady-state history plots of the feedwater and superheated steam flow rates, temperatures, water level and drum pressure. Steady-state calculation was performed for 5,000 sec and the set-point values of the control systems were reached. The first 1,000 sec of calculation showed that there were no significant difficulties to reach steady-state conditions. As it can be verified after about 1,500 sec of calculation, the steam boiler parameters reach steady-state and the regulation system included in the model accelerate the achievement of the steady-state.

Trasient description and initials conditions: In spite of the radiant steam boiler to be inherently safe, situation that can disturb the normal steam boiler operation are possible to occur. Therefore, several transient events were already observed during normal operation of such facilities. As example, ruptures and leakage from pipes and valves which are located in the main steam and feedwater lines. The transient studied here is a partial loss of feedwater by a rupture in the tube situated at the feedwater line from economizer to steam drum. The equivalent total section of the break is 50.26 cm^2 corresponding to the diameter of 80 mm.

Initial conditions at the initiating event onset were determined by pre-transient steady-state calculations reported in the previous section. The main steady-state thermal-hydraulics parameters of the steam boiler at time of transient initiation were shown in Table 2. The model used to simulate the break on each individual tube is composed of a trip-valve conditioned by a signal connecting the tube to a time dependent volume (Fig. 4). After 50 sec of steady-state operation of the steam boiler, the transient was initiated by an instantaneous opening of the valve.

Table 3: Imposed sequence of events

Time	Imposed events
-50-0 sec	Steady-state regime
At 0.0 sec	Break opening
t very low water level (315 mm)	Alarm signal is generated
After 1 sec	Burners shutdown
At 200 sec	Feedwater pump cost down
At 1000 sec	End of transient

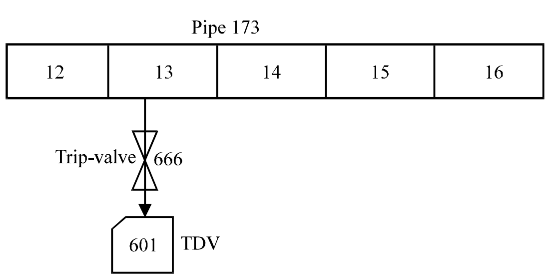

Fig. 4: Nodalization scheme of the break

The tube rupture induces immediately a sudden decrease in the steam drum water level. When it drops below 315 mm, a low-low water level alarm signal is generated and the burners will stop immediately. The imposed events involved in this transient are outlined in Table 3. The heat inertia due to the hot gases heat capacitance is considered. In order to take into account, the air cooling mechanism and the heat flux density ratio is represented by a negative value.

RESULTS AND DISCUSSION

The transient test scenario is modeled using the Relap5/Mod3.2 computer code and the industrial radiant steam boiler ABB ALSTOM. The calculation was performed up to 1000 sec of the transient time. Before running the investigated transient event, the Relap5/Mod3.2 Model was run in real plant equilibrium conditions up to 50 sec to establish steady-state conditions at nominal steam boiler load. The initiating event of this analysis is the steam generator tube rupture in feedwater line from economizer to steam drum.

The main parameters transient curves describing the steam boiler behavior before and after the break accident are shown in Fig. 5 through 10. The transient calculation results are given through the steam boiler thermal-hydraulic parameters: pressure, water level, temperatures, void fraction and mass flow rates.

Figure 5 shows the feedwater and outlet steam flow rates variation during the transient. At steady-state, the feedwater and the steam flow rate are equal to 374 time h^{-1}. At the break opening, the steam flow rate drops to 338 time h^{-1} after that and due the burners stopping, the steam flow rate brutally vanishes. It is shown that the feedwater flow rate increases after the accident to achieve a maximum of 555 time h^{-1} at

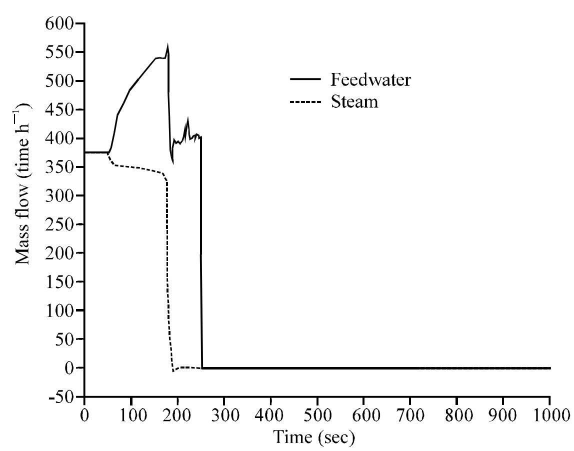

Fig. 5: Feedwater and steam flow rates variation

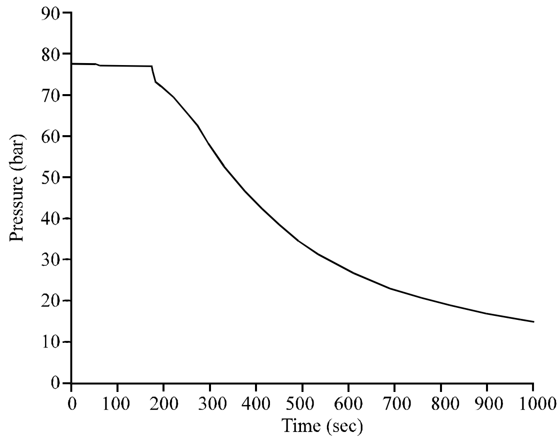

Fig. 6: Steam drum pressure variation

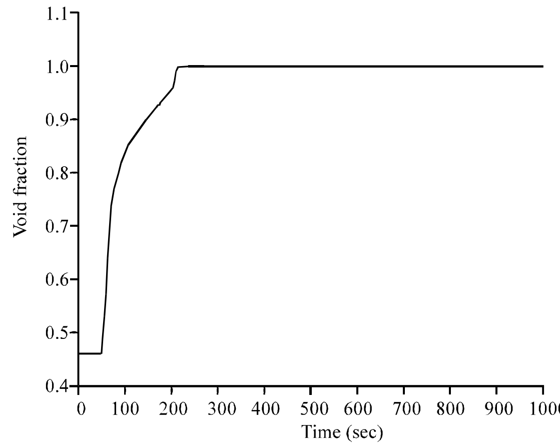

Fig. 8: Drum void fraction variation

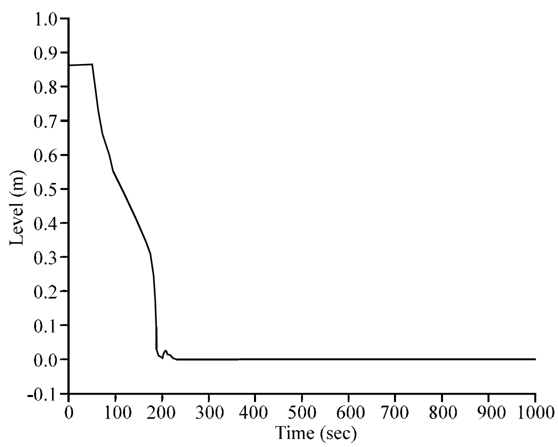

Fig. 7: Drum water level variation

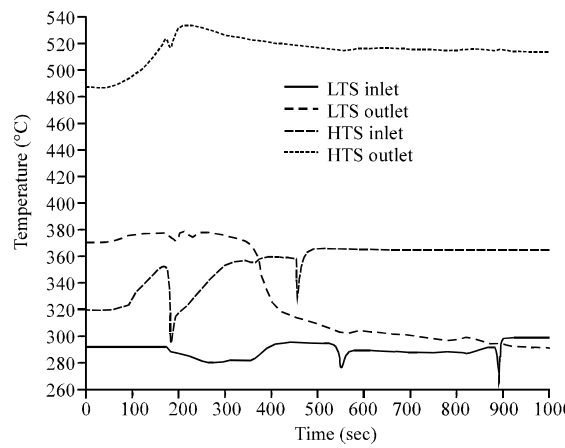

Fig. 9: Steam temperature variation at the inlet and outlet of the high and low temperature superheaters

175 sec, the increase in the feedwater flow rate is governed by the automatic feedwater control valve response which acts to maintain the water level in the steam drum. According to the imposed events for this scenario, the feedwater pump stops running at 200 sec then the feedwater flow rate decrease immediately until it vanishes.

The steam drum pressure variation during accident is shown in Fig. 6. Due to the fast opening of the break and because of the release of water, the steam drum pressure drops from 77.3-76.7 bars; it remains at this value until the end of the transient. Then, it decreases by normal depressurization of the steam boiler associated to the cooling of the whole facility by the external air cooling. Figure 7 shows the predicted steam drum water level during the transient.

At first, the water level decreases from its set point value of 0.86-0.315 m during 175 sec. At this time, the burners automatically shutdown then the water level decreases rapidly to vanish during 22 sec and it remains at this value until the end of the transient. The decrease in the water level is a consequence of the system depressurization (Fig. 6) caused by the break opening. It is important to investigate the void fraction variation during the transient to well understand the tow phase flow behavior in the steam boiler. Figure 8 shows the variation of the void fraction in the steam drum. Following the break opening, the void fraction in the drum starts to increase until reaching 92% according to the decrease of the mass flow rate (Fig. 5) associated to the steam boiler depressurization caused by the break. After that, the void fraction increases instantaneously to reach the unit as result to the vapor generation suppression inside the steam drum and stabilizes to this value until the end of the transient.

Figure 9 shows the steam temperature variation at the inlet and outlet of both high and low temperature superheaters (LTS & HTS) after the beak opening. It is clear that at the outlet of each superheater, the steam

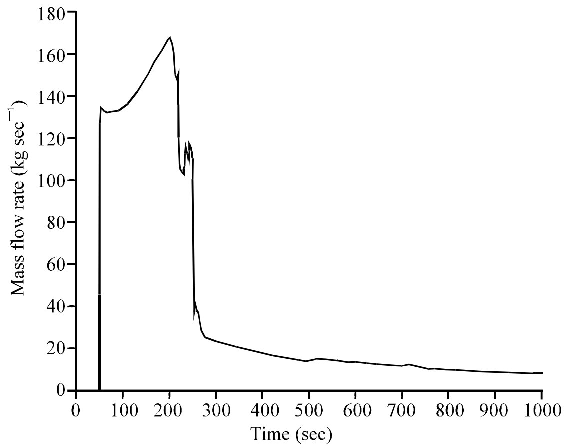

Fig. 10: Leak flow rate variation

temperature varies strongly depending on the steam flow rate. After shutdown of the burners, the temperatures continue to rise caused by the heat inertia of the hot gases. After that because of the imposed air cooling on the external walls, the temperatures start to decrease slowly. It is of interest to evaluate the flow rate predicted at the tube rupture.

The leak mass flow rate variation during accident is shown in Fig. 10. At the accident occurrence, the leak flow rate increases instantaneously to 133 kg sec^{-1}. After that it remains at its maximum value till 199 sec and then, it decreases due to the burners shut down. This decrease is the consequence of the pressure drop following the burners' shutdown leading to an intense production of steam. Later, it falls proportionally to the pressure until the end of the transient.

CONCLUSION

The purpose of this study is to investigate the thermal-hydraulic behavior and response of the industrial radiant, natural circulation steam boiler under steady-state and tube rupture accident using the thermal-hydraulic code system Relap5/Mod3.2. The accident scenario analyzed includes a break of a single tube in the feedwater line from economizer to steam drum.

A complete plant model has been made, improved and validated against available plant data. A good agreement between the numerical results and the steam boiler operating data for the steady-state is obtained. During the transient, the thermal-hydraulic parameters: flow rates, drum water level and pressure, temperature at the inlet and the outlet of both high and low temperatures superheaters, void fraction variation and leak flow rate are used to assess the system response to the accident and how control systems can successfully mitigate the consequences. The steam boiler Relap5 Model has proved satisfactory and the model was capable of predicting all of thermal-hydraulic transient features of the radiant steam boiler. The obtained results demonstrate the Relap5 code capability to predict the main phenomenon taking place in whole system of the steam boiler. Models of this nature have short computing time and are particularly useful for simulators where a real time is desired.

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ABBREVIATIONS

RELAP5: Reactor Excursion Leak Analysis Program 5eme Version
HTS: High Temperature Superheater
LTS: Low Temperature Superheater
ECO: Economizers
LWR: Light Water Reactor
INEL: Idaho National Engineering Laboratory
NRC: Nuclear Regulatory Commission
TDV: Time Dependent Volume
PI: Proportional Integral

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