Transient simulation of an industrial steam boiler

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Abstract: The safety analysis of an industrial installation is extensively based on modeling and simulation. However, the analysis of simulation using realistic computer codes like RELAP5/Mod3.2 will help understand thermal-hydraulic behavior of an installation during normal and accidental conditions. In a steam boiler operation, it is very important to evaluate numerous accident scenarios under real plant conditions. One of the main accidental transients is tube rupture of steam boiler. The main objective of this study consists to investigate the behavior of an industrial steam boiler installed in the complex of natural gas liquefaction (LNG) at Skikda in Algeria during feed water line break accident. A RELAP5 model was set up to simulate the entire system, the model represents all steam boiler components to be suitable for the analysis of the several accidents. The control and regulation systems are also considered. The model was qualified against the steam boiler data at steady-state conditions. As seen from the results, a good agreement was obtained. The transient simulation results show that the thermal-hydraulic code correctly predicts the behavior of the main steam boiler parameters and how the control system, when required, can successfully mitigate the accident.

Keywords: Industrial Steam boiler; Safety; Modeling and simulation; Relap5; Steady-state validation, Tube rupture transient

1. INTRODUCTION

In industry, natural circulation water tube steam boiler account for a significant part of the fuel consumed in a plant [1], they have a large range of applications such as industrial heating processes and power cycles due their advantageous features [2]. Nevertheless, such installations are subjected to numerous operating failures that could expose the system structural integrity to serious hazard and enormous human life and economic losses [3]. A frequent steam boiler fault is the tube rupture in the down comer and riser sections due to thermal stress and aging. Early detection of such faults in operation is important to reduce productivity loss caused by unscheduled steam boiler shutdown and possible damage to equipments, thus ensuring the safety of the installation [4].

Numerous experimental and numerical investigations have been realised to study the thermalhydraulic behavior of an installation, but they highly based on expensive experimentation and building scaled models. But nowadays, the advances in the computer technology have made it possible to carry out complex calculations and even faster than real time using mathematical modeling and computer simulation like system codes, they are widely used in the domain of facilities safety assessment [5, 6].

The main objective of this work is modelling and simulation of an industrial steam boiler during feedwater line break accident using RELAP5 thermal-hydraulic computer code.

The steam boiler is a water tube natural circulation type. It is a part of natural gas liquefaction (LNG) complex at Skikda in Algeria [7].

A detailed model of steam boiler installation is developed based on RELAP5 code including all components. The elaborated model is validated against steady-state parameters of steam boiler at different loads. After the establishment of a steady-state regime in the installation, the transient of the tube water leakage is simulated by an instantaneous rupture occurring with an equivalent diameter of 90 mm located at the level of the feedwater line at the outlet of the economizer.

2. STEAM BOILER PRESENTATION

The studied steam boiler is installed in the complex of natural gas liquefaction (LNG) at Skikda in Algeria (operated by SONATRACH company) designed to produce 374 tons/h of superheated steam at 73 bars and 487°C with 92 % of the thermal efficiency [7, 8 & 9]; its role is to assure the supply of the plant with superheated steam for driving a turbine.

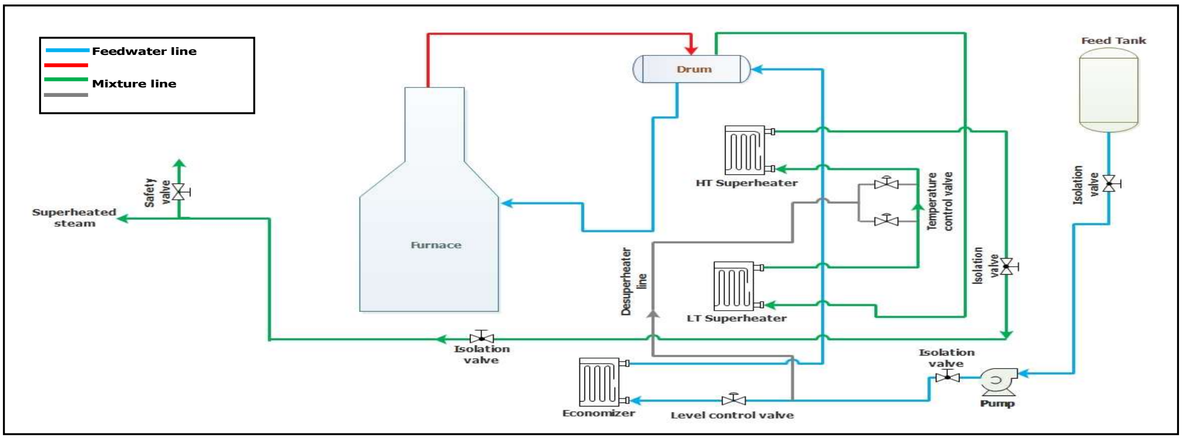

Fig. 1 Representation diagrame of the installation.

Table 1 Operating characteristics of steam boiler

Technical parameters	Unit	Values
Steam flow rate	t/h	374
Drum pressure	bar	79.6
Feedwater inlet temperature	°C	118
Air excess in the furnace	%	1.3
Efficiency	%	92

The steam boiler is principally composed of three parts: the steam generator, the main feedwater and the main superheated steam pipelines as it is presented in the Fig.1. The steam generator consists of one drum, combustion chamber, 12 burners at three levels, downcomers and rear pass which receive two superheaters and three economizers.

The monitoring and control systems of the steam boiler include several safety systems to prevent damage during normal and abnormal operations. Two safety valves are installed on the main superheated steam pipeline; the top of the drum is equipped with three safety valves that control pressure and four isolation valves and four flapper valves in different emplacements. The steam boiler is designed to be operated by combination of an automatic and manual operation. The main steam boiler operating parameters are presented in Table 1.

The dominant heat transfer in the furnace is radiation, while, conduction and convection contribute less than 5% of the heat transfer [10]. The fumes leaving the combustion chamber is transferred by convection to the rest of the steam boiler components (economizers and superheaters tubes). A more detailed presentation of the steam boiler is given in Ref [7].

3. MODELING AND SIMULATION

Relap5 presentation

The thermalhydraulic system code RELAP5 was developed at the Idaho National Engineering Laboratory (INEL); it is a best estimate nuclear system code. RELAP5 is a generic code that, in addition to calculating the behavior of a nuclear system during an accidental transient, can be used for simulation of a wide variety of thermal and hydraulic transients in both nuclear and nonnuclear system involving mixture of water and steam. RELAP5 includes numerous generic components models from which general systems can be modeled like pumps, valves, pipes, heat structures, separators, control system components, etc. The code is based on non-homogeneous and no-equilibrium hydro-dynamic model for the two phase system solved by a partially implicit finite difference numerical method. The general solution procedure using RELAP5 is to subdivide the installation into a number of control volumes connected by junctions. The conduction heat transfer model is one-dimensional, using a staggered mesh to calculate temperatures and heat flux vectors [11, 12].

Steam boiler nodalisation

In this section we give a description of the nodalization of the steam boiler model, the RELAP5 model was developed for analyses of operational occurrences, design basis scenarios and abnormal events. Information and data for the modeling of this system were obtained from the steam boiler documentation and from the facility staff.

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. We used the component Servo-valve 011 to simulate the drum water level control valve, and Motor-Valve 003 for the isolation valve. The economizer is modeled by PIPE component 171 using 41 volumes, 40 junctions, and 20 heat structures. The main steam pipeline is modeled by PIPE components 302-311, and the BRUNCH 083, 084, 085, 086. The superheaters SBT and SHT are modeled respectively by PIPE components 176 and 180 using 16 volumes, 15 junctions, and 20 heat structures for each one. The regulation valves of steam temperature are modeled with two servo-valves 012 and 013. The isolation valves are modeled by motor-valve 001 and 002. 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 desuperheater pipeline is modeled using the PIPE components 320, 321, 322, 324 and 325. The control system used in the system 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 *Steamctl* component to control the steam temperature and *Feedctl* component to control the level of water in the water drum. The heat densities involved between the fumes and the external tube surface are imposed. The nodalization diagram of the installation is presented in Fig.2.

Validation

The nodalization may be considered validated when it reproduces the measured steady-state condition of the system, it has a geometric fidelity with the installation and it demonstrates satisfactory time evolution conditions [13, 14]. The nodalization validation is performed by comparing the model prediction with the operating data, in this work; it was compared with steady-state operating condition at three different loads of 60%, 100% and 110%. As it can be seen in Table.II, the RELAP5 results compared to each other are in good agreement and the calculation errors remain in acceptable margins. On the other hand, the regulation systems for the outlet superheated steam temperature and the water level were considered in order to achieve a satisfactory steady-state. Thus, according to RELAP5 users [13], the developed model could be considered as qualified at steady-state level since the obtained accuracy at steady-state level between the simulation results against plant data is acceptable.

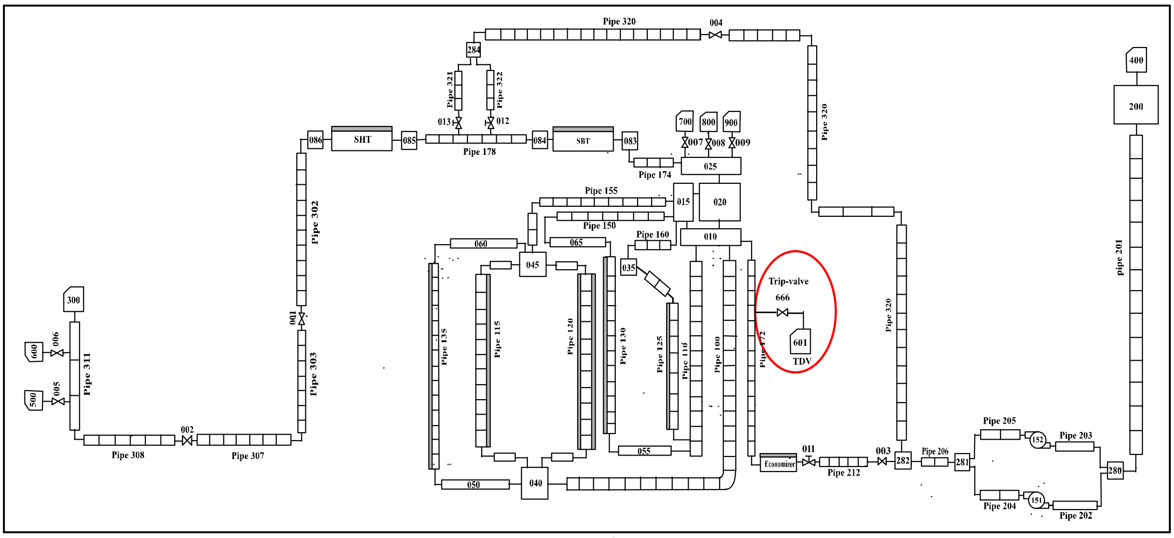

Fig. 2 Nodalisation diagram of the steam boiler system.

Table 2 COMPARISON BETWEEN RELAP5 AND THE OPERATION DATA.

		60 % load		100 % load		110 % load	
Thermal hydraulic parameters	***Unit***	***Design***	***Relap5***	***Design***	***Relap5***	***Design***	***Relap5***
Exit steam flow rate	t/h	224.400	224.363	374.000	374.357	412.000	412.289
Feedwater flow rate	t/h	224.400	224.364	374.000	374.121	412.000	412.583
Desuperheater flow rate	t/h	8.000	6.721	25.000	26.043	25.000	24.335
Outlet steam temperature	°C	288.000	289.087	292.000	292.368	293.000	293.668
Inlet LTS superheater temperature	°C	288.000	289.108	292.000	292.316	293.000	293.594
Outlet LTS superheater temperature	°C	356.000	357.019	370.000	370.848	374.000	373.247
Inlet HTS superheater temperature	°C	330.000	333.827	322.000	320.141	321.000	329.084
Outlet HTS superheatertemperature	°C	487.000	487.493	487.000	487.338	487.000	487.217
Feed water inlet temperature	°C	118.000	120.591	118.000	119.000	118.000	119.432
Outlet economizer temperature	°C	263.000	262.863	287.000	287.030	293.000	292.893
Drum water level	mm	860.000	859.998	860.000	860.003	860.000	860.084
Pressure at collection tank	bar	1.890	1.890	1.890	1.890	1.89.000	1.890
Drum pressure	bar	74.770	73.542	76.900	77.200	78.139	78.695
Inlet steam generator pressure	bar	82.000	75.154	82.000	78.200	82.000	80.312
Vapor pressure	bar	71.720	72.176	73.000	73.199	73.42	74.407
Inlet pump pressure	bar	2.900	2.590	2.910	2.587	2.900	2.586
Outlet pump pressure	bar	91.900	96.410	91.900	94.150	91.900	93.473

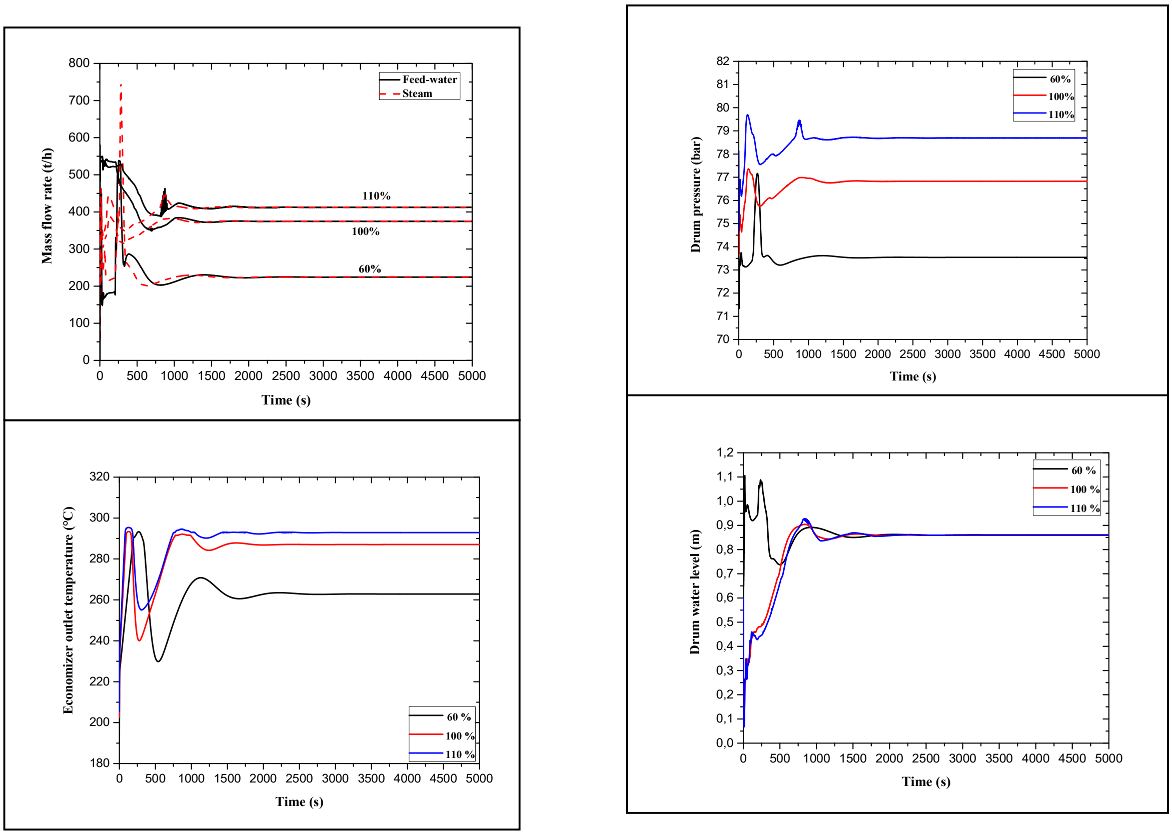

FIG. 3 EVOLUTION OF SOME STEAM BOILER PARAMETERS AT DIFFERENT LOADS DURING STEADY-STATE.

4. INITIAL CONDITIONS AND TRANSIENT DESCRCIPTION

Although an industrial steam boiler to be inherently safe, situations which disturb its normal operation may occur. Numerous accidental events were already observed during normal operation of such installations. As example, ruptures and leakage from pipes which are located in the main feed water and steam lines.

The transient studied in this investigation is a partial loss of feedwater by a rupture in the tube situated at the exit of the economizer with an equivalent total break section of

63.61 cm2 corresponding to the 90 mm diameter.
The rupture is modelled using a Trip-Valve conditioned by a signal connecting the break location on the tube to a Time-Dependent-Volume (Fig.2).
To perform the transient calculation, it is necessary to verify Initial conditions at the initiating event onset were determined by pre-transient steady-state calculations. For this purpose, the simulation of the transient is preceded by a steady-state period of 50 s. The main steady-state steam boiler thermalhydraulic parameters were summarized in Table 2.

At 50 s of steady-state operation, the transient was initiated by an instantaneous full opening of the valve used for the break simulation. The tube break induces immediately a decrease in the water level. A low water level alarm signal is generated when it drops below 315 mm and the steam boiler will shutdown immediately. The transient imposed events are outlined in Table 3. The heat inertia due to the fumes heat capacitance and the air cooling mechanism are considered.

Table 3 IMPOSED SEQUENCE OF EVENT

Time	Imposed events
0-50 s	Steady-state conditioning
At 50 s	Break opening
Reached of low water level (315 mm)	Alarm signal is generated
After 1 s	Burners shutdown
200 s	Feedwater pump cost down
800 s	End of transient

5. RESULTS ANALYSIS AND DISCUSSION

The transient event is modeled using the RELAP5 computer code and an industrial steam boiler. The calculation was performed up to 700 seconds of the transient time. Before running the transient calculation, the RELAP5 model of the steam boiler was run in real facility equilibrium conditions up to 50 seconds to establish steady-state conditions at 100 % steam boiler load. The transient calculation of this analysis is the steam boiler tube rupture in feedwater line at the exit of the economizer. The main parameters describing the steam boiler behavior before and after the accident are presented in Fig.4 – 9.
It is very important to evaluate the break mass flow rate during the transient, it is given in Fig.4. At the accident occurrence, the leak flow rate rises instantaneously to 133 kg/s. Then, it remains at its maximum value till 199 seconds (167 kg/s), after that, it drops due to the pressure drop following the burners' shutdown leading to an intense production of steam. Thereafter, it chutes proportionally to the pressure until the end of the transient.

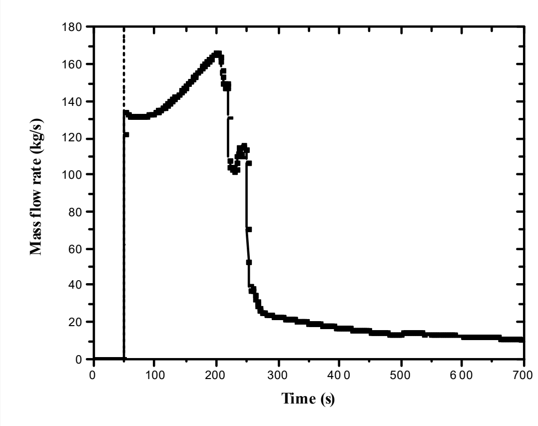

Fig. 4 Leak mass flow rate.

Figure.5 shows the predicted steam drum water level during the transient. At the beginning, the level of water decreases from 0.86 m (set point value) to 0.315 m during 175 seconds. At this moment, the burners automatically shutdown then the water level drops rapidly to vanish during 22 seconds. This decrease is a consequence of the system depressurization (Fig.6) caused by the rupture opening.

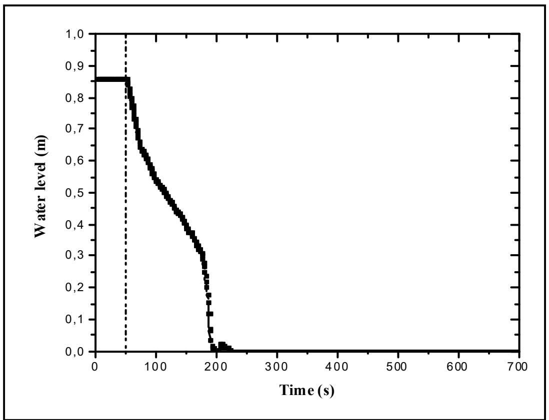

Fig. 5 Drum water level.

The steam drum pressure evolution during transient is given in Fig.6. Due to the break opening and the release of water, the steam drum pressure decreases from 77.3 bars to 76.7 bars; and it remains at this value until the end of the calculation. After that, it decreases due to the normal depressurization of the steam boiler associated to the whole facility cooling by the external air.

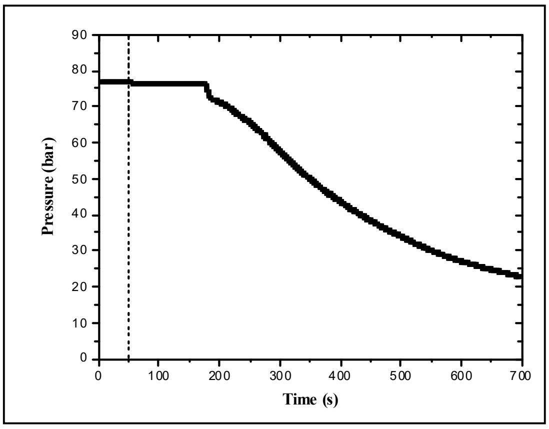

Fig. 6 Steam drum pressure.

Figure.7 illustrates the void fraction evolution in the steam drum during the transient in order to well understand the tow phase flow behavior in the steam boiler. After the break opening, the void fraction in the drum starts to rise until reaching 92 % according to the water level decrease (Fig.5). This is due to the steam generation under feedwater rate leak where evaporation is feed by steam boiler water. After the burners stopping, the steam generation vanishes instantly and steam drum water flows down to feel the void issuing from phase separation.

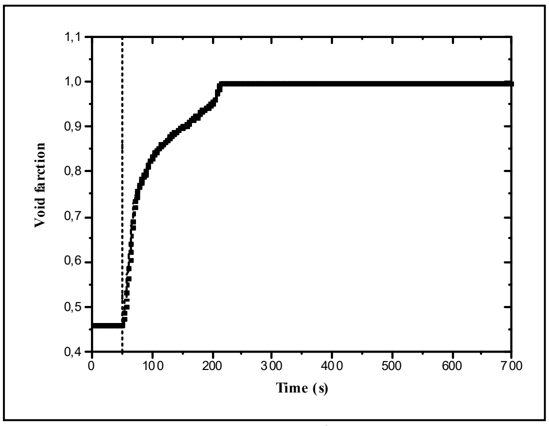

Fig. 7 Drum void fraction.

The inlet and outlet steam temperature of both superheaters (LTS & HTS) during the transient are given in Fig.8. It is clear that the steam temperature varies strongly at the outlet of each superheater depending on the flow rate of the steam. After burners shutdown, the temperatures continue to increases due to the heat inertia of the hot fumes. Thereafter, the temperatures commence to decrease slowly due to the imposed air cooling on the external walls.

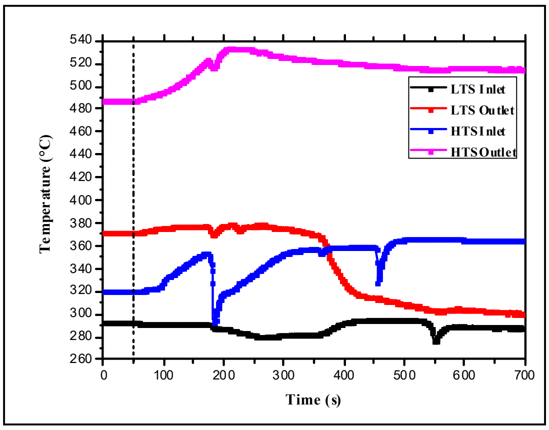

Fig. 8 Steam temperature at the inlet and outlet of the superheaters.

In Fig.9 we give the feedwater and steam flow rates variation during the accident. During the steady-state operation, the feedwater and the steam flow rates are equal to 374 t/h. At 175 seconds after the accident, the feedwater flow increases to achieve a maximum of 555 t/h, this increase is due to the automatic feedwater control valve response which acts to maintain the water level in the drum. According to the imposed events, at 200 seconds, the feedwater pump stops running which induces a decrease in the feedwater flow rate until it vanishes. Moreover, the steam flow rate at the break opening drops to 338 t/h, after that it brutally vanishes due the burners stopping.

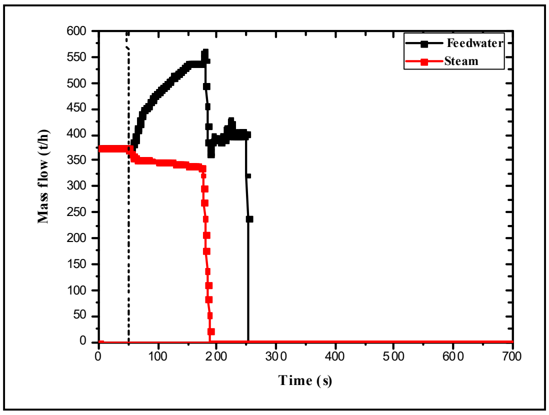

Fig. 9 Feedwater and steam flow rates.

6. CONCLUSION

The main objective of this study is to investigate the thermalhydraulic behavior of an industrial natural circulation steam boiler under a tube rupture transient using the thermalhydraulic system code RELAP5. The scenario of the accident includes a break of a single tube in the feedwater line at the exit of the economizer. A whole facility model has been built and validated against available operating data of the steam boiler. A good agreement between the RELAP5 results and the experimental data for the steady-state is obtained. During the transient, the main thermalhydraulic parameters are used to assess the steam boiler behavior to the accident and how control systems can successfully mitigate the consequences accidentals. On the other hand, the steam boiler RELAP5 model has proved satisfactory, and the model is capable of predicting all of accidental thermalhydraulic transient. Moreover, the obtained results demonstrate that RELAP5 code is capable to predict the main phenomena that can occur in whole system. Models of this type have short computing time and are very useful for simulators where a real time is desired.

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