Research Article

Modeling and simulation of a natural circulation water-tube steam boiler

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Abstract

In the present work, the overall behavior of a steam boiler is investigated using RELAP5/MOD3.2 system code at three different operating loads. Main thermal–hydraulic parameters are analyzed at steady-states corresponding to 60%, 100% and 110% of the boiler nominal load. RELAP5 system code is widely used in the design and safety analysis of nuclear reactor installations as well as for conventional facilities in recent years. The steam boiler studied herein is a water-tube natural circulation type used in a natural gas liquefaction complex for superheated steam production purposes. A complete model of the steam boiler has been developed for the RELAP5 code. This model, that is also suitable for transient simulation, has been used for the reconstruction of three steady-state tests in order to assess the steam boiler safety features during the operation. The model includes all parts that can eventually influence the safety of the steam boiler particularly the control and regulation system. A qualification process has been undertaken in the aim to verify the capability of the model to reproduce the main parameters of the steam boiler. This process revealed that RELAP5 system code results matches significantly the experimental data of the steam boiler. Finally, it should be mentioned that the results obtained so far are very encouraging for studying the general behavior of the steam boiler in transient operating conditions, as well as for evaluating its safety under hypothetical scenarios. This step will be undertaken in the near future and will allow the check of the code capability to simulate thermal–hydraulic phenomena occurring in the steam boiler during transient operation.

Keywords Steam boiler · Natural circulation · RELAP5 · Model qualification · Steady-state simulation

Abbreviations

Q_{fur}	Furnace transferred heat
Q_{Tot}	Total exchanged power
Q_{Eco}	Transferred heat to economizers
Q_{HTS}	Transferred heat to high temperature superheater
Q_{LTS}	Transferred heat to low temperature superheater
q	Heat flux density
S	External heat exchange surface
m_{fuel}	Fuel air mass flow rate
m_{air}	Air mass flow rate
m_{gas}	Fume mass flow rate
Cp_{gas}	Fume heat capacity
Cp_{air}	Air heat capacity
T_{out}	Outlet temperature
T_{inl}	Inlet temperature
T_{air}	Inlet air temperature
T_{gas}	Exhaust fumes temperature
LCV	Natural gas fuel lower-calorific value

1 Introduction

Steam is a powerful heat transfer medium which is largely used in industrial plants. It is cheaper for production and distribution compared to other heat transfer medium [1]. Steam production and utilization techniques are important aspects of engineering technology. Therefore, the steam generators are of capital importance for thermal power installation, they are a widely used for energy

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conversion equipment that transforms chemical energy into thermal energy to generate steam especially in the liquefaction [2]. Recently, industrial water-tube steam boilers have received great attention due to their benefits like simplicity, low costs and more particularity inherent safety [3]. A boiler is the complex multivariable system in the thermal power plant involving many components and phenomena, considering the phase change, nonlinear and the inverse response behavior (swell and shrink). From another side, it is necessity to control the steam boiler operating conditions since the temperature and pressure variation inside the combustion chamber affects the boiler's safety and efficiency. They can be considered as the main causes of plant explosion. Special attention is therefore paid to their safety in order to guarantee their reliability and stability in the event of an accident.

Moreover, it is very difficult to carry out tests and make measurements directly on the steam boiler due to dangers from the operating conditions and economical constraints [4]. Furthermore, the search for the optimum operating conditions and the way to control them is not an easy task. In practice, safety assessment and prediction of real behavior of plant process under normal and transient conditions usually uses computational methods, which made it possible to perform complex calculation efficiently and even faster than real time.

The commonly used modeling and simulation tools are principally based on the progress of programming, the numerical methods development and the provision of powerful computing resources [5]. Several numerical and analytical investigations have been carried out in order to study the behavior of steam boilers. Liu et al. [6] used neural networks techniques for modeling a 1000 MW ultra super-critical-coal fired boiler. The validated model and the results of simulation demonstrated the advantages and efficiency of the neural network method in boiler modeling. Backi [7] introduces a nonlinear approach to determine the medium enthalpy dynamics between the inlet of heater water (economizer) and the outlet of once-through boiler evaporator. Dhanuskodi et al. [8] developed a supercritical steam boiler model to predict the temperature of the tube inner wall using artificial neural networks. The model takes into consideration the steady-state distribution of fluid operating conditions like pressure and temperature. A non-linear hydrodynamic model of a supercritical pulverized coal-fired boiler was developed by Pan et al. [9]. It is based on the momentum, mass and energy conservation equations and uses the quasi-Newton method to solve iteratively the equations which produced heating surfaces thermal-hydraulic characteristics. Hajebzadeh et al. [10] developed a 320 MW tangentially steam boiler model at steady-state in different partial loads to evaluate several parameters effect on the operation of the equipment of the steam boiler. The model is composed of sub-models and used the Newton–Raphson method for numerical resolution of equations. Sreepradha [11] has developed a simple integrated model based on mass and energy equations for the economizer, superheater and drum. The simulation results (pressure and temperature) were compared to the operating parameters of a power plant. Grądziel [12] has developed a mathematical model of a natural circulation boiler evaporator who describes the thermal phenomena that occur in the evaporator. This model is experimentally qualified for various boiler operation states. A methodology for hydraulic calculations of water–vapor flow and evaporation for both forced and natural circulation loops is presented by Tucakovic et al. [13], so, a steam boiler analysis was performed for the whole range of facility working loads. Beyne et al. [14] presented a steady-state and thermal dynamic model for heat transfer in the steam boiler in order to estimate the peak load capability and sizing novel designs of boiler. Mathematical model of a 765 MW Thermal power station was carried out by Kocaarslan and Çam [15] based on the measurements in various operation points of the plant. After that, this model was used to apply various adaptive control strategies. Dhruvi et al. [16] has developed a simulator for static and dynamic classifiers types of coal-pulverizers, which is based on the mass and heat balance equations. This model is simulated in Matlab/Simulink platform. Dong et al. [17] presented a numerical calculation of hydrodynamic characteristic using a loop analysis method of a natural circulation steam boiler, thus, it was confirmed that this method can enhance the hydrodynamic characteristic calculation reliability. At different boiler loads, Wu et al. [18] established a thermal–hydraulic calculation model for the medium temperature platen superheater in a 300 CFB steam boiler considering both thermal and hydraulic non-uniformity. Xiaojing et al. [19] has built a model of a 2953 t/h ultra-supercritical once-through steam boiler to study the vertical water wall hydraulic characteristics using the Chebyshev polynomial fitting method.

Most of the previous investigations are based firstly on the homogeneous model with thermal and mechanical equilibrium between the two phases of flow and secondly on geometric and phenomenological simplifications of the system, which makes these models incapable of predicting complex situations such as swelling and settling phenomena. The calculation of complex situations requires the use of appropriate calculation tools based on physical models describing these phenomena as well as possible. That's why we used the RELAP5 system code, which is known for its robustness in modeling such phenomena.

To make a safety evaluation of a plant, it is necessary to study its normal and accidental global thermal–hydraulic behavior [20]. In practice, a model representing the plant is developed and qualified at the steady-state level [21]. The model once qualified is then used to perform the necessary calculations, especially at the transient state level, permitting to bring a clear answer to the safety issues of the plant.

In this paper, a detailed RELAP5 model of the steam boiler plant is developed including all components (main feedwater pipeline, steam generator and main superheated steam pipeline). The RELAP5 model is qualified against steady-state values at different loads (60%, 100% and 110%) using operational plant data collected from the steam boiler unit [22]. The qualification results are in good agreement confirming the model validity to predict the plant performance at various loads and are very encouraging in view of the constraints imposed by the steam boiler installation intricacy. In the following sections, we present the steam boiler characteristics, the nodalization of its different parts and finally the simulation results with some discussions.

2 Steam boiler presentation

The NGL complex which is operated by SONATRACH Company, located at 5 km east side of Skikda, Algeria and it has been in production since 1970 [22]. The complex contains six units, each one equipped with a steam boiler, to provide superheated steam primarily for driving a turbine therefore making energy available to the unit [22].

The steam boiler under consideration is a radiant water-tube natural circulation type, delivering the same power and used to replace the previous D-type one damaged during the 2004 explosion [23]. It generates 374 tons/h of superheated steam at 487 °C and 73 bars with about 92% of the design thermal efficiency. The steam boiler plant consists primarily of three main parts: the steam generator, the feedwater line and the steam pipelines (Fig. 1) [23].

The steam generator consists of two main parts; the combustion chamber and the rear pass materialized by the water walls that form the vaporizer tubes. The upper part of the common wall between the furnace and the rear pass allows the circulation of the combustion gases between the tubes which are disjointed. The rear pass is equipped with superheaters at the top and the economizers at the bottom. This steam generator contains a single drum and collectors of water and water mixture (water/steam). The water extracted from the drum is fed by five external drop tubes, four of them are used to feed the combustion chamber and the remaining one feeds the rear pass. The water/steam mixture coming from the combustion chamber and from the rear pass circulates towards the drum in a total number of 74 tubes. There are 20 tubes feeding superheaters, which conduct saturated steam from the drum to the inlet collector of the primary superheater (LTS).

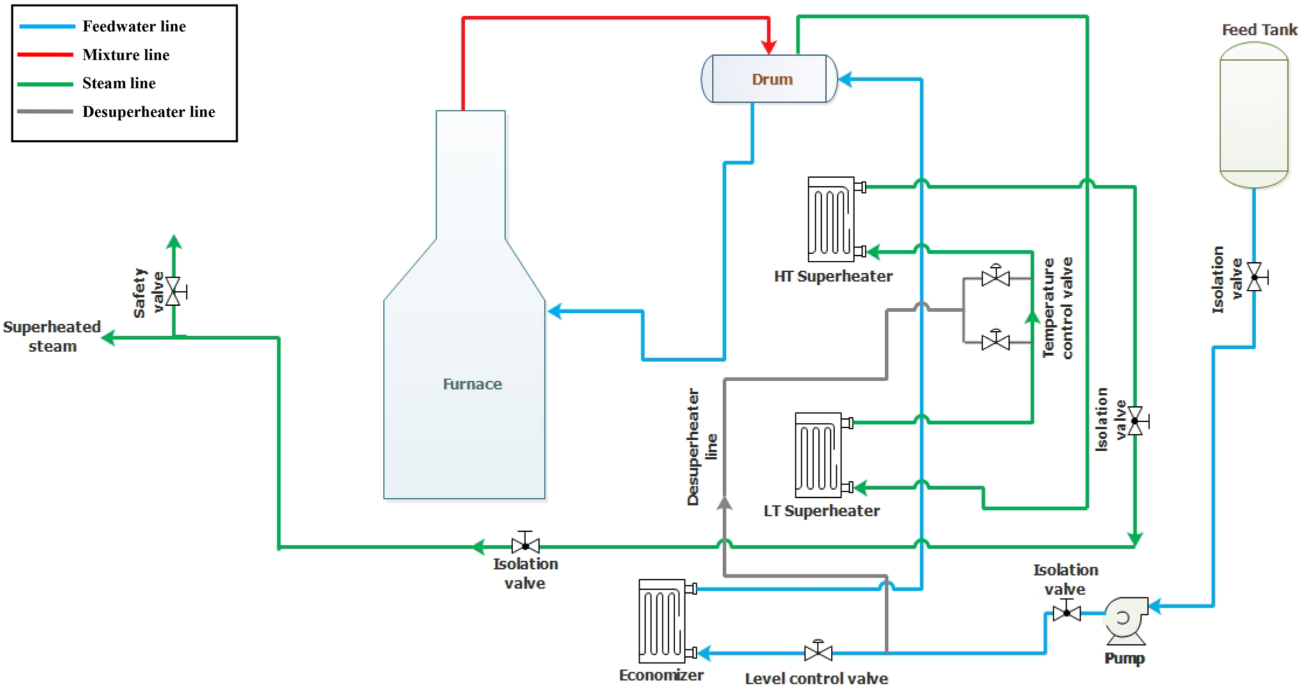

Fig. 1 Entire plant diagram

The combustion chamber is a large metal volume of 7637 mm in length, 16,627 mm in height, and 7853 mm in width, wherein the mixture of air and fuel burns and provides the heat necessary to produce steam. It consists of finned tube panels joined together, forming corrugated membranes on the six faces of the furnace. The water walls role inside the furnace is mainly to generate steam and at the same time to maintain the temperature far below the melting value of the tubes metal.

Radiation is the predominant mode of heat transfer in the combustion chamber of a radiant steam boiler, as indicated by its name. Therefore, the heat introduced into the combustion chamber (Fig. 2) is divided into two parts:

- Heat transferred to the fluid directly from the walls.
- Heat evacuated by the flue gas at the exit of the combustion chamber.

The heat received by water walls is conducted through the membranes and tubes walls, and transferred by forced convection in nucleate boiling to the water/vapor mixture in the vaporizing tubes [23].

The steam generator includes a single drum (big horizontal tank), with a total length of 11,700 mm and a diameter of 1830 mm. The drum has function to provide the reserve water necessary for the permanent supply of the evaporator beams and receives the water/steam mixture from them. At the top, it is equipped with a compartment containing two rows of baffles, whose role is to release steam from water droplets that are entrained by the steam. In this type of drum (Fig. 3), there are no separation cyclones, but it is done in a natural way. In addition, three safety valves are placed on the top of the tank to purge the drum in the case of vapor pressures respectively equal to 86, 85.5 and 85 bars.

The set point of the water level in the drum is 860 mm. During normal operation, it must be kept between the high level (1115 mm) and the very low level (315 mm) [24]. It is measured by level transmitters, based on the principle of differential pressure measurement between a reference column and the height of the water in the drum. Two control valves on the feedwater collector are used to adjust the water level.

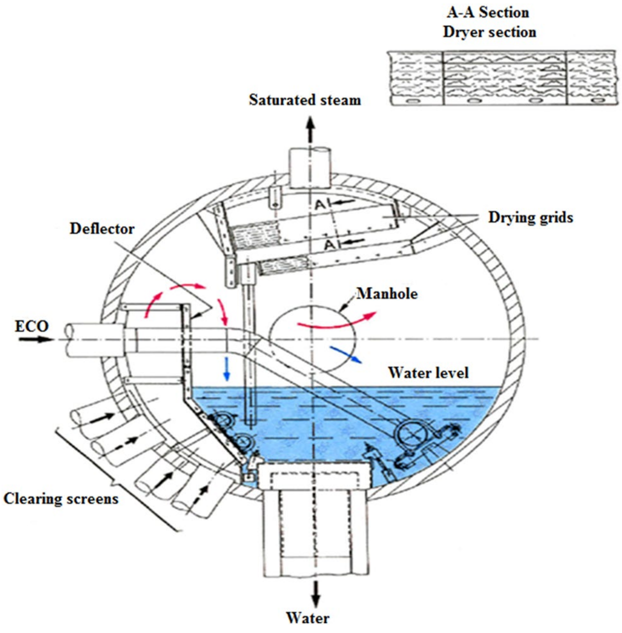

Fig. 3 Steam boiler drum

There are three economizers (two are finned and the third is smooth) placed in the rear pass at the bottom of the steam generator. The economizers recover residual energy from the flue gases leaving the furnace and use it to heat feedwater before entering the drum in order to maximize thermal efficiency and reduce heat emissions. The thermal–hydraulic parameters of the economizers are grouped in Table 1 [22].

The steam generator contains two superheaters placed in the upper part of the rear pass connected in series; one operates at low temperature (LTS), and the other one at high temperature (HTS). They are used to increase the

Fig. 2 Thermal balance in the furnace

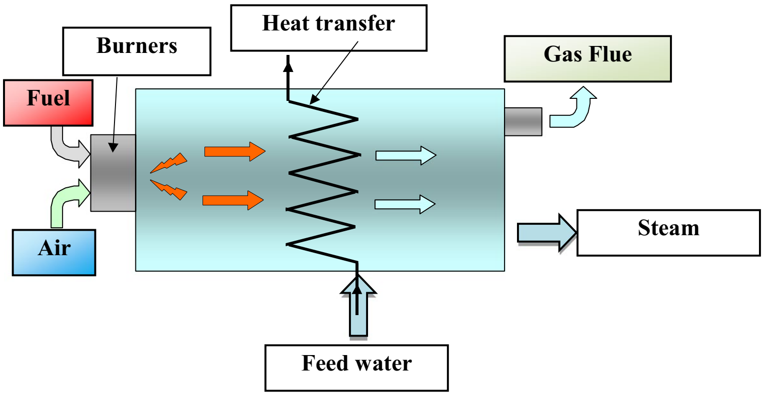

Table 1 Thermal–hydraulic parameters of economizers

Thermal–hydraulic parameters	Unit	Values
Feedwater inlet temperature	°C	118
Feedwater outlet temperature	°C	287
Fumes inlet temperature	°C	653
Exit fumes temperature	°C	188
Feedwater mass flow	t/h	349
Fumes mass flow	Nm^3/h	390,499

Table 2 Thermal–hydraulic parameters of the superheaters

Thermal–hydraulic parameters	Unit	Values
LTS Inlet steam temperature	°C	292
LTS outlet steam temperature	°C	370
HTS Inlet steam temperature	°C	322
HTS outlet steam temperature	°C	487
HTS Fumes inlet temperature	°C	1147
HTS Exit fumes temperature	°C	853
LTS Outlet fumes temperature	°C	653
Superheated steam mass flow	t/h	349
Fumes mass flow	Nm^3/h	390,499

temperature of the saturated steam leaving the drum up to 487 °C. The superheaters receive heat by convection from the fumes exiting the combustion chamber; the temperature variation of the steam through the superheaters is shown in Fig. 4. The superheated steam temperature is controlled by a desuperheating water injection performed at the inter superheaters collector using two desuperheating valves with identical characteristics that are operating in cascade [22, 23]. The superheaters thermal-hydraulic parameters are mentioned in Table 2.

3 Modeling and nodalization

3.1 Description of the code

RELAP5 is mainly used for the design and safety analysis of nuclear plants, advanced fluid systems and experiments [25, 26]. The aim of the RELAP5 code development effort from the beginning was to produce a code that includes important first-order effects necessary for accurate prediction of system transients [27]. RELAP5 allows for the simulation of probable thermal–hydraulic transients in nuclear facilities under a large variety of postulated accident conditions such as loss of coolant, loss of flow, power excursion as well as operational transients and other postulated transients [28]. In addition, it can be used for wide range of thermal–hydraulic transient simulation in nonnuclear plants involving mixtures of steam and water; it is a highly generic code [29]. The two-phase non-homogeneous, non-equilibrium six equations are used as a basis for the hydrodynamic model and are formulated by volume and time averaged parameters and solved by a fast partially implicit finite difference numerical method [30]. The code includes several generic models allowing the simulation of different types of components of an installation [27], like pipes, pumps, turbine, valves, heat structures, separators, and control system. The simulation of a system consists firstly of subdividing it into control volumes interconnected by flow junctions; this for convenience of INPUT [30].

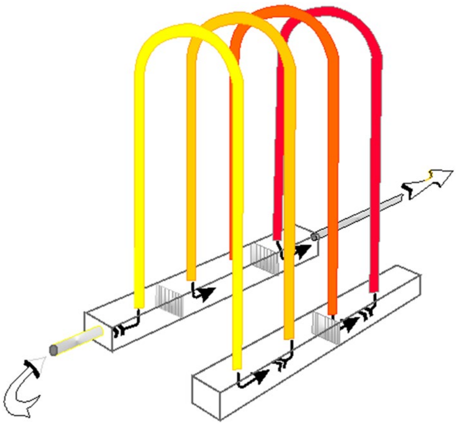

Fig. 4 Steam temperature variation through the superheaters

3.2 Steam boiler nodalization

The modeling of industrial installations such as a steam boiler requires a thorough and detailed knowledge of all its components; as well as all the physical phenomena that occur throughout the system. A detailed model of a natural circulation water-tube boiler unit is developed using RELAP5/MOD3.2 including all the main components (steam generator, drum, heat exchangers, pipeline of steam and feedwater, and regulation and control system). The steam boiler model was developed from documented plant design, performance data reference and staff [22]. The steam boiler modeling strategy is based on the following steps:

- Preparation of geometric, thermal–hydraulic and technical data describing the entire system.
- Nodalization of the hydrodynamic circuit of the installation into control volumes connected by junctions.
- Control and regulation system modeling.

- Boundary and initial conditions simulation of the installation, pressure, temperature, mass flow, and heat flux at the heat exchangers and combustion chamber.
- Validation and qualification of the theoretical results of the code compared to operating data for the boiler at steady-state conditions.

Data preparation and collection needs considerable effort due to the great amount of data and information on each component to be included in the model. Nodalization is the first step of the steam boiler simulation. It aims to define all the hydraulic characteristics of the installation such as geometrical data, diameters, elevations, roughness of pipe walls, length, and concentrated or distributed losses coefficients and so on. It should be noted that supplemental efforts have been made to overcome some difficulties encountered during this study, like the unavailability of some geometrical data.

The main RELAP5 components used in the boiler nodalization are presented hereafter:

- PIPE: for those portions of the system without branches.
- BRANCH: to model interconnected piping networks.
- TIME DEPENDENT VOLUME: for the imposed thermodynamic data (pressure and temperature), and when velocity or mass flow of fluid is known.
- VALVE: used for regulation, safety and isolation.
- PUMP: to simulate the centrifugal pump.
- JUNCTION: used to connect other components such as two pipes.
- TRIP AND CONTROL SYSTEM: used to perform actions such as opening or closing a valve and stopping a pump.
- HEAT STRUCTURE: to simulate the heat transfer between the fluid and the tubes walls.
- GENERAL TABLE: to impose the density of thermal flux.

The main features of the developed model are summarized below:

- Number of control volumes: 582.
- Number of junction: 589.
- Number of heat structures: 142.
- Number of mesh point in heat structures: 2840.
- Number of time dependent volumes: 7.
- Number of logical trips: 17.
- Number of control variables: 39.

The steam generator part is modeled with 188 control volumes, 191 junctions and 69 heat structures. The drum, also called upper tank, is the seat of many physical phenomena such as water/steam separation and steam condensation. It is therefore very important to follow some best practices for its nodalization to reproduce all these phenomena. The approach used to model this tank involves subdividing it into four components "BRUNCH": 010, 015, 020, and 025. The feedwater and water/steam emulsion collectors are modeled using ten "BRUNCH" components: 030, 035, 040, 045, 050, 055, 060, 065, 070, and 075. PIPE 100 represents the four downpipes that feed the furnace, and the PIPE 110 is the central downpipe that feeds the rear pass. The tubular screens that constitute the furnace and the rear pass are modeled via the component "PIPE", the vaporization tubes of the front and rear screens of the combustion chamber are grouped and modeled by the "PIPE" components 115 and 120 respectively, and for the side screens by the pipe 135. Rear pass vaporizer tubes are modeled by the "PIPE" components 130 and 125. The tubes that feed the drum with feedwater leaving the economizer are modeled by PIPES 172 and 173. The water/steam emulsion tubes coming out of the front and rear pass going to the drum are modeled by the PIPES 150, 155, 160 and 165. The 20 tubes of saturated steam coming out of the drum going to the superheaters are modeled by the PIPE 174. There are three safety valves installed on the drum, they are modeled by the "TRIP-VALVE" components 007, 008 and 009 respectively connected by the components "Time Dependent Volume" 700, 800, and 900 to impose the atmospheric conditions [31]. The heating tube is modeled by the heat transfer component (heat structure) maintained at a constant heating rate as a boundary condition. The nodalization scheme of the steam generator is presented in Fig. 5.

The steam generator contains five heat exchangers, among them two superheaters are operating at high and low temperatures respectively in addition to two finned economizers and a smooth one. These three economizers are lumped in one tube and nodalized by the "PIPE" component 171 using 41 control volumes, 40 junctions and 20 heat structures. The inlet and outlet collectors are modeled respectively by "BRUNCH" components 070 and 075. The low and high temperature superheaters are modeled by "PIPE" components 176 and 180 respectively, each using 20 heat structures, 16 control volumes and 15 flow junctions. The inlet and outlet collectors of each superheater are modeled respectively by the "BRUNCH" components 083, 084, 085, and 086; the inter-superheater tube is modeled by the "PIPE" component 178. Figure 6 shows the representative heat exchangers nodalization diagram. Desuperheating section in the portion of the pipe that connects the main line of feedwater and the inter-superheaters line where the superheated steam temperature regulation is done by the injection of feedwater. This desuperheater is modeled by the "PIPE" components 320, 321, 322, 324 and

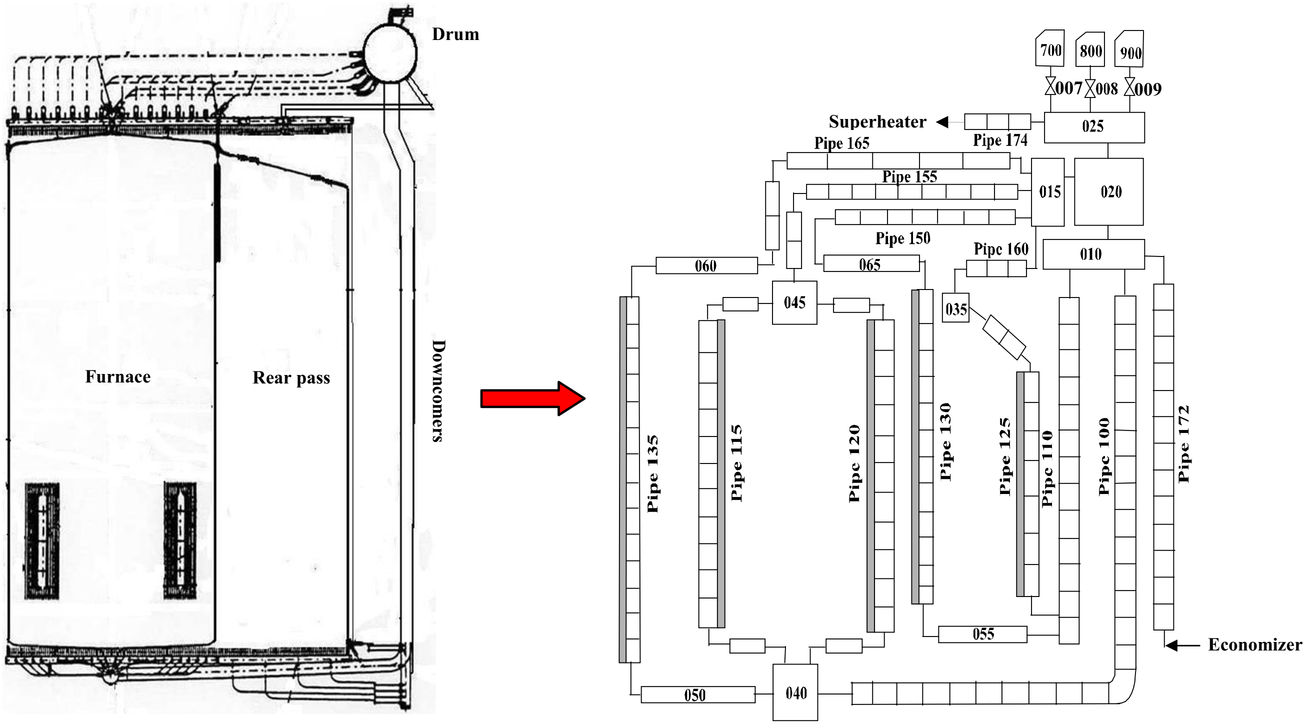

Fig. 5 Steam generator nodalization

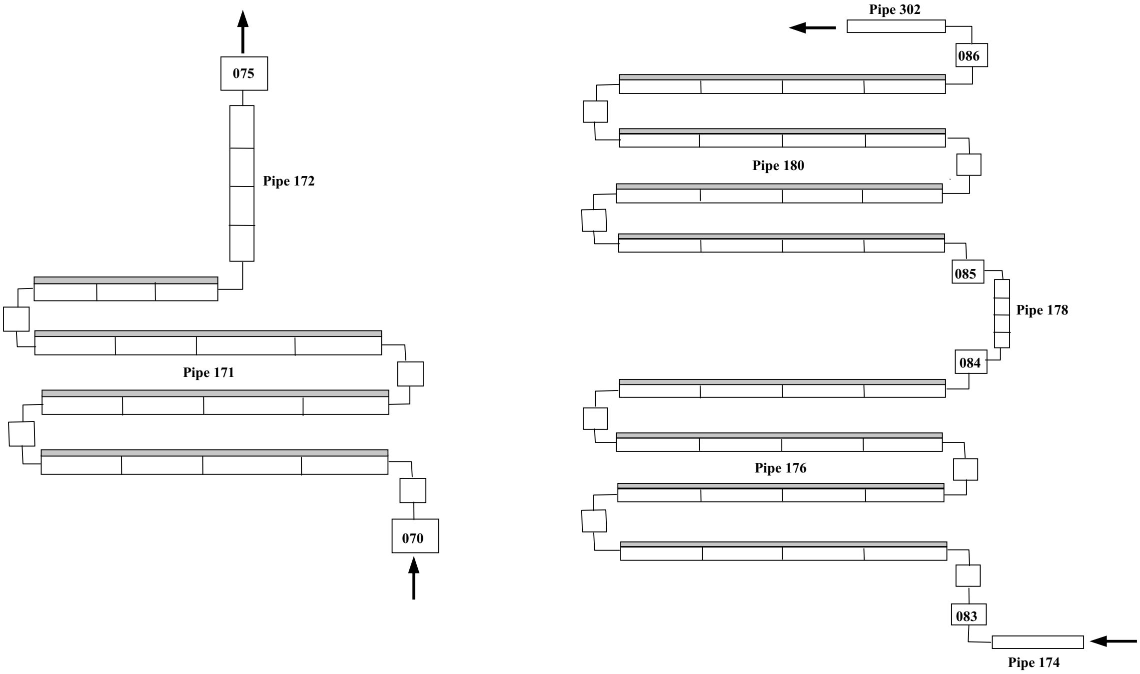

Fig. 6 Nodalization of the heat exchangers

325, and the “BRUNCH” 284 (Fig. 7). The isolation valve on the desuperheating line is modeled by the “TRIP-VALVE” component 004.

The main feedwater line includes collection tank (modeled by the component “BRUNCH” 200), two centrifugal feed pumps (modeled by the “PUMP” components 151

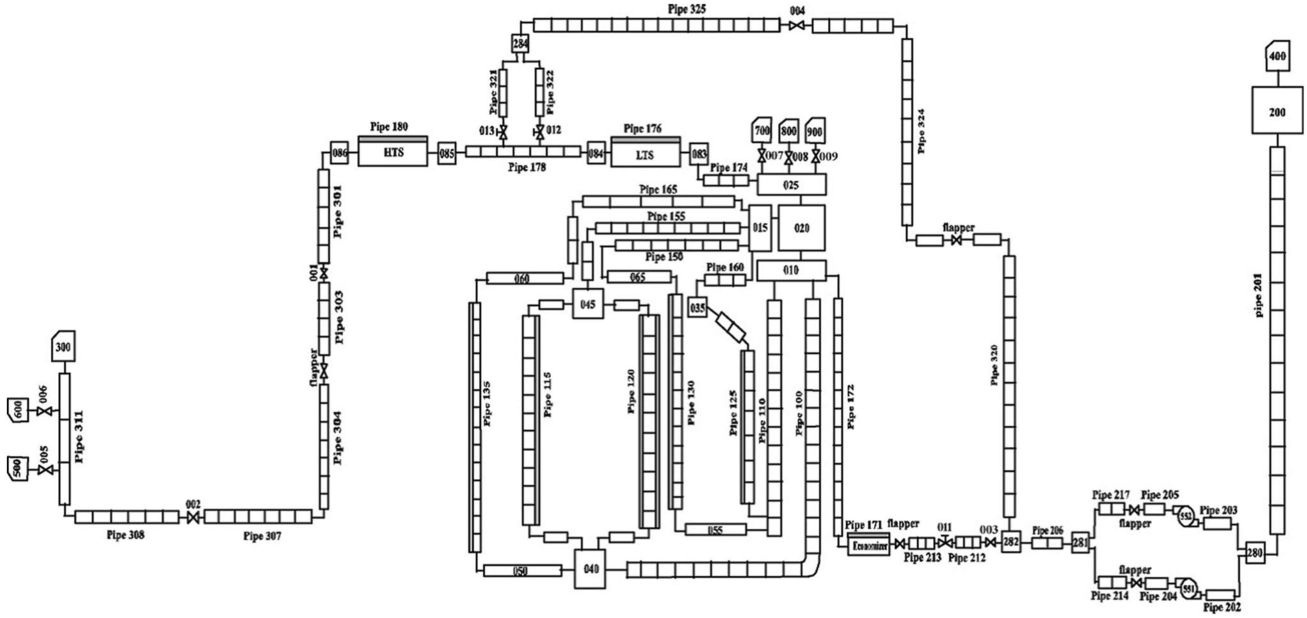

Fig. 7 Steam boiler system nodalization diagram

and 152), pipes that feed the steam generator through the feedwater are modeled by the "PIPE" components 201 through 218 and "BRUNCH" components 080, 081 and 082, and control and isolation valves. This line is modeled by 157 control volumes and 150 junctions. The flappers which are at the outlet of the pump and at the steam boiler inlet as well as at the desuperheating line are modeled respectively by the components "CHECK-VALVE" 215, 216, 219, and 323. The "TRIP-VALVE" component 003 is used to simulate the isolation valve at the inlet of the economizer. The control valves of water-level in the drum are modeled by the "SERVO-VALVE" components 011 and 010.

The main line of superheated steam is modeled by the "PIPE" components 301through 311 and the steam isolation valves are modeled by the "TRIP VALVE" components 001 and 002. The safety valves installed on the main steam line are modeled by the "TRIPE-VALVE" components 005 and 006 that are connected to "TMDPVOL" components 500 and 600 respectively. The control valves of superheated steam temperature are modeled using the "SERVO-VALVE" components 013 and 012, and the flapper is modeled by the "CHECK-VALVE" component 391.

The regulation has a vital role in the operation and prevention of industrial plants. To achieve a stable and safe operation of an energy system it is recommended to use an automatic control loop in order to maintain the stability of the plant in normal and abnormal operation. The steam boiler is controlled to provide superheated steam at a temperature of 487 °C and a pressure of 73 bars; therefore, the control systems in the plant include two loops of regulation, one for the superheated steam temperature and the other for the water level.

The purpose of the controller is to bring the drum water level up to a set point of 860 mm and maintain it for a desired steam load. The "FEEDCTL" component is used to model the regulation of the water level in the drum. It calculates the position signal of the feedwater regulating valve, which is modeled by the "SERVO-VALVE" component 011. In fact, the regulation controls the water level in the drum by actuating the main valve by combining based three parameters: the flow of feedwater, the flow of superheated steam and the drum water level.

The purpose of regulating the temperature of superheated steam is to maintain a constant temperature value (487 °C) at the steam boiler outlet by injecting desuperheating water into the collector between the superheaters using two identical redundant desuperheating valves. Modeling regulation systems and loops is possible using RELAP5 code special components such as "STEAMCTL" component which is used to control the superheated steam temperature. The regulation process compares the average steam temperature at the outlet of the superheater HTS to the set point (487 °C) and the generated signal is used to control valves 013 and 012 opening.

Thermal–hydraulic conditions associated with the fluid are set up using "TMDPVOL" and "TMDPJUN" components connected to the boundaries of the circuit. The pressure and the temperature of the fluid at the inlet and outlet of the steam boiler are respectively imposed by "TMDPVOL" components 400 and 300.

Heat transfer phenomena in the steam boiler are modeled using RELAP5 heat structures modeling process. The structures simulating the heat transfer in the steam boiler are connected with pipes 130 and 125 for the rear pass, with pipes 135, 120 and 115 for the furnace, and with pipes 180 (HTS), 176 (LTS) and 171 (Eco) for the heat exchangers respectively. The operating data presented previously in Tables 1 and 2 are used to estimate the total power generated in the steam boiler as well as the heat (Q) transferred through each heat transfer region. The external heat transfer surface (S) is used to calculate the heat flux densities using the relation q = Q/S [20]. The heat flux densities involved between the external tube surfaces and the hot gases are imposed by table entry. The heat flux table is entered as the right boundary conditions for simulating the radiation heat transfer for the furnace. The heat exchange for the economizers and superheaters is transferred by convection to the remainder of the superheaters and the economizers using thermal energy of the flue gas exiting the furnace. The heat flux densities at the heat exchangers are determined using an energy balance of the flue gases between the inlet and outlet of each heat exchanger as shown in Fig. 8

$$Q = m_{gas}Cp_{gas}\left(T_{out} - T_{inl}\right) \tag{1}$$

Q_{fur} is the heat transferred in the combustion chamber calculated using the relation:

$$Q_{fur} = Q_{Tot} - \left(Q_{Eco} + Q_{HTS} + Q_{LTS}\right) \tag{2}$$

While Q_{HTS}, Q_{LTS} and Q_{Eco} are the heat transferred in the high temperature superheater, low temperature superheate and economizers respectively, and Q_{Tot} is the total exchanged power deduced by the relation [20]:

$$Q_{Tot} = m_{fuel}LCV + m_{air}Cp_{air}T_{air} - m_{gas}Cp_{gas}T_{gas} \tag{3}$$

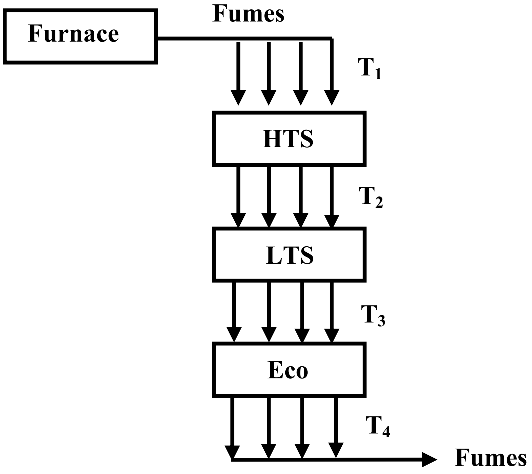

Fig. 8 Steam boiler energy balance

where m_{fuel} and m_{air} are respectively fuel and air mass flow rates, LCV is the natural gas fuel lower-calorific value, Cp_{gas} and Cp_{air} are respectively the heat capacity of gases and air, T_{air} is the inlet air temperature, and T_{gas} is the exhaust fumes temperature. Table 3 shows the calculated heat flux densities associated with the heating surfaces of each screen.

4 Results and discussion

4.1 Model qualification

In view of a subsequent use of the current model for a the safety evaluation of the steam boiler, its qualification at the steady-state level is necessary before simulating any postulated transitional operating condition. To perform this qualification process, the main parameters of the steam boiler were analyzed at three different power levels, namely 60%, 100% and 110% of its rated operating load. Some of these parameters were selected to demonstrate the steady-state establishment as shown in Fig. 9. According to the simulation results, the steady-state is achieved after running the code for 5000 s. The stable operation of the steam boiler around the set point values is clearly seen showing the appropriateness of the way the different controllers were modeled. The oscillations observed during the first 1500 s on the different curves correspond to the search for normal operating conditions from the quantities introduced as initial conditions.

The steam boiler RELAP5 model is considered qualified once it reproduces with acceptable error margins the normal operation parameters compared to the experimental data [20]. Table 4 shows a comparison of the main thermal–hydraulic parameters calculated by RELAP5 code against the steam boiler operating data at the corresponding operating conditions. As it can be seen, there is a good agreement between the results and the calculation errors remain within acceptable margins. Of course, this is achieved through the adequate modeling of the controllers that played a great role in achieving the steady-state with reasonable running time, namely the regulation loops for the water level and the outlet superheated steam temperature. From this analysis and in order to perform the

Table 3 Heat flux density imposed on the surface in contact with the fumes

	Furnace	Rear pass	Eco	LTS	HTS
Heat structure	135, 115, 120	130, 125	171	176	180
Flux density (kW/m^2)	162	23	34.35	34.97	60.54

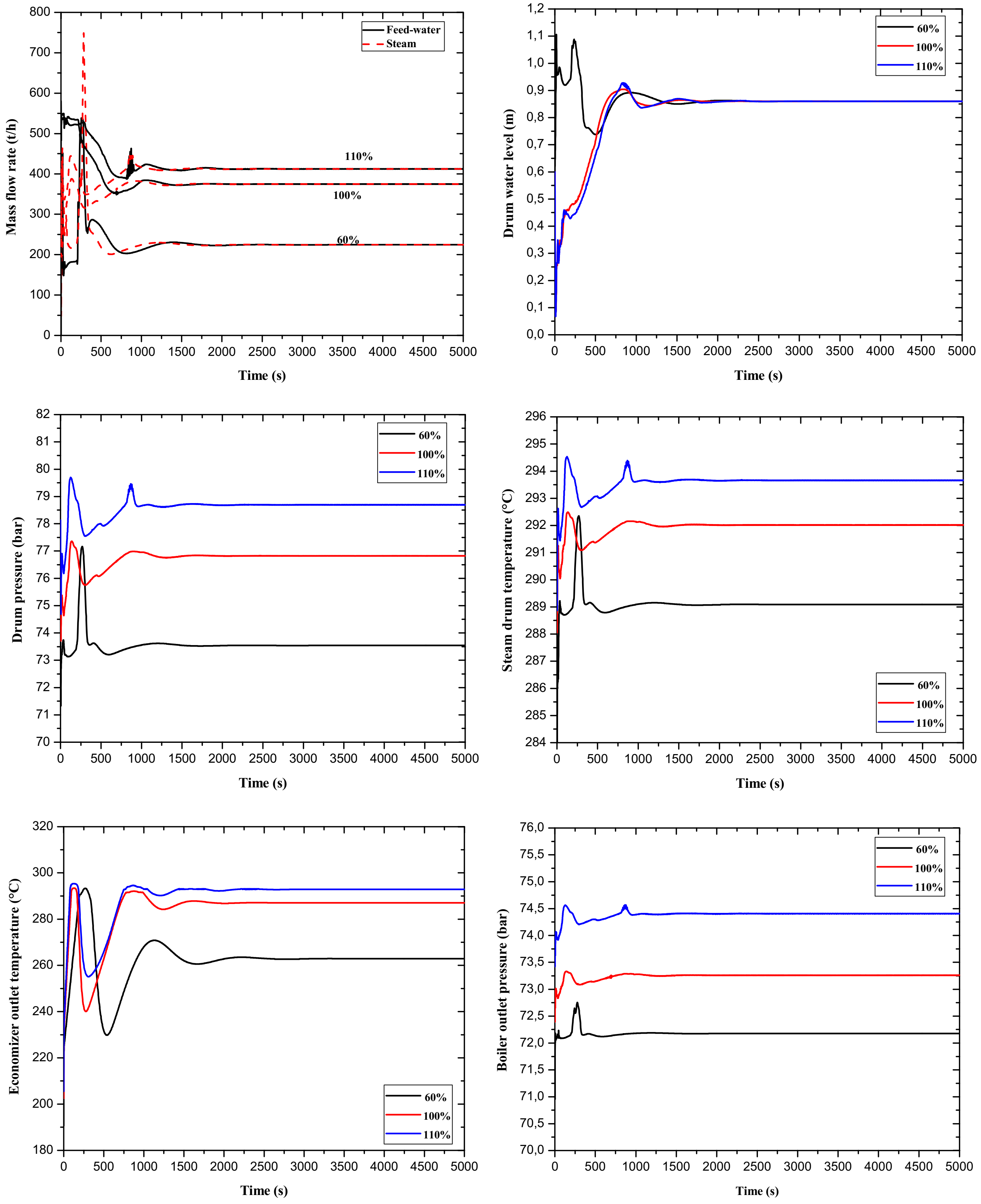

Fig. 9 Temporal evolution of some steam boiler parameters at different loads

Table 4 Comparison between the theoretical results and the operating data

Thermal–hydraulic parameters	Unit	60% load		100% load		110% load	
		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

subsequent calculations, the steam boiler RELAP5 model is considered qualified at the steady-state level [32].

4.2 Thermal–hydraulic characteristics

To understand the behavior of the steam boiler, it necessary to quantify the thermal–hydraulic parameters and to track them during the whole simulating process, particularly during a transient operating condition. A qualitative and quantitative analysis of the simulation results is presented in this section in order to examine the thermal–hydraulic behavior of the fluid in every component of the steam boiler (the drum, the furnace, the rear pass, and the downcomer). Table 5 represents the calculated results obtained at the steady-state level for the three operating loads. The results clearly express the steam boiler thermal–hydraulic behavior according to the boundary conditions and following a change in the working load. The vapor mass flow rate inside the vaporizer tubes is well predicted showing its increase following an increase in the steam boiler total load.

Figures 10, 11, 12, 13, 14, and 15 show the axial distribution of the temperature, heat transfer coefficient, void fraction, and pressure as well vapor and liquid velocities of the fluid along the rear screen of the combustion chamber. We note that RELAP5 results concerned only the heated part of the pipe.

For safety purpose and to ensure the steam boiler plant reliability, the metal temperature of all the heat surfaces must be kept under the safety limitation [19] which is around 500 °C [22]. Figure 10 shows the distribution of the internal and external temperatures of the vaporizer tube wall as well as the fluid temperature. It is obvious that outer wall temperature is higher than inner one due to the high radiation heat flux caused by the burners. As it can be seen, a distinct region of high wall temperature appears in the height range from 2 to 3 m, where the inner and outer wall temperatures reaches respectively a maximum value of 330 °C and 305.6 °C for 110%, 325.5 °C and 303.5 °C for 100%, 312 °C and 297.7 °C for 60%. These results show that the maximum wall temperature remains lower than the safety limitation even if the operation load is 10% above the normal operation one. Thus, the steam boiler unit can operate safely under these conditions. We also note that the temperature profiles are influenced by the change of configuration between the vertical and horizontal parts for the vaporizer tube.

Concerning the distribution of the fluid temperature inside de vaporizer tube, the fluid gradually heats from the inlet to the outlet, conveying the heat produced by the wall. This increase in temperature is the result of forced convection heat exchange between the inner tube surface and the fluid. Moreover, the fluid temperature increases with the load rise. In steam boilers with natural circulation, the vaporization process is by nucleate boiling to ensure continuous cooling of the heated wall of the tubes by water [33]. As long as this vaporization regime is maintained, the internal temperature of the wall remains higher than the fluid saturation temperature. According to Fig. 10, the heat transfer inside the furnace tubes is ensured by the nucleate boiling regime which is characterized by a

Table 5 Main simulation parameters at different parts of the steam boiler

Thermal-hydraulic parameters	60% load	100% load	110% load
Front screen of furnace (pipe115)			
Mass flow rate, kg/s	187.06	191.13	196.73
Average fluid temperature, °C	290.04	293.07	294.73
[a]Internal wall temperature, °C	291.68	295.35	297.17
Void fraction, %	31.66	49.24	48.64
Pressure, bar	74.56	77.837	79.75
Rear screen of rear pass (pipe125)			
Mass flow rate, Kg/s	78.579	84.242	85.889
Average fluid temperature, °C	289.68	292.70	294.37
[a]Internal wall temperature, °C	292.39	295.07	297.02
Void fraction, %	15.41	17.62	18.50
Pressure, bar	74.16	77.44	79.30
Lateral screen of rear pass (pipe130)			
Mass flow rate, Kg/s	81.965	82.060	82.265
Average fluid temperature, °C	289.87	292.88	294.53
[a]Internal wall temperature, °C	292.40	295.38	297.08
Void fraction, %	20.04	23.28	23.94
Pressure, bar	74.28	77.58	79.45
Lateral screen of furnace (pipe135)			
Mass flow rate, Kg/s	353.03	368.95	370.58
Average fluid temperature, °C	289.82	292.84	294.51
[a]Internal wall temperature, °C	297.29	302.60	304.73
Void fraction, %	34.82	46.47	49.13
Pressure, bar	74.23	77.53	79.41
Downcomer pipe100			
Mass flow rate, Kg/s	753.85	754.84	757.12
Average fluid temperature, °C	287.55	291.69	293.76
Pressure, bar	74.64	77.91	79.77
Steam drum (brunch 020)			
Pressure, bar	73.55	76.83	78.70
Temperature, °C	289.17	292.82	293.84
Void fraction, %	45.94	45.93	45.93

[a]Last volume of the pipe

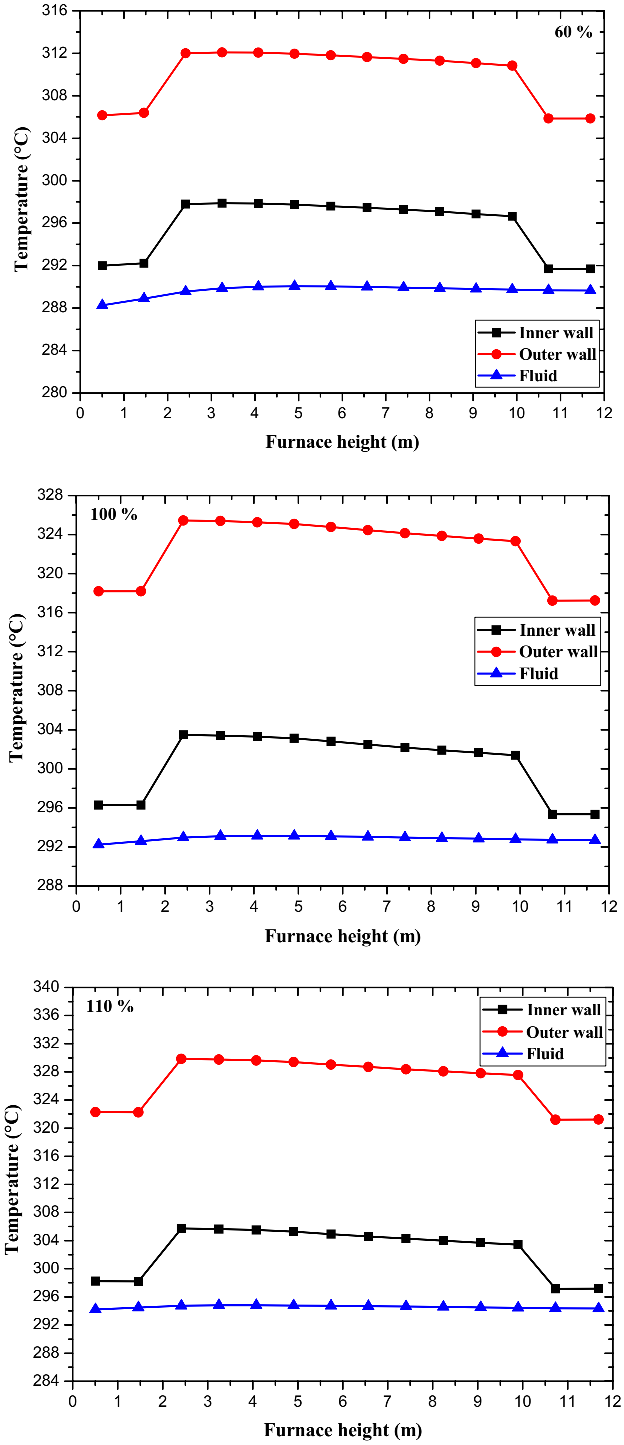

Fig. 10 Temperature distribution along the furnace tube length

fluid saturated temperature, a moderate temperature of internal wall and a good heat transfer coefficient (Fig. 11).

Figure 11 depicts the distribution of the heat transfer coefficient along the furnace height. Heat transfer coefficient in nucleate boiling region mainly depends on heat flux, thus, an increase in heat flux (loads increase) causes an increase in two phase boiling heat transfer coefficient [34], as illustrated in Fig. 11. After a slight linear increase in heat transfer coefficient in the single phase liquid region it drops until it reaches 24.3 kW/m^{2}K, 23.66 kW/m^{2}K and 23.90 kW/m^{2}K respectively, then, it increases linearly again. The maximum values of the heat transfer coefficient have been observed at a height of 10 m of the vaporizer tube. They are 62.7 kW/m^{2}K, 74.7 kW/m^{2}K and 77.8 kW/m^{2}K corresponding to the boiler loads of 60%, 100% and 110% respectively. On the other hand, it can be seen, from the same figure, that the heat transfer coefficient is influenced by the configuration change between the horizontal and vertical parts of the vaporizer tube. Indeed, the heat transfer coefficient is more significant in horizontal part

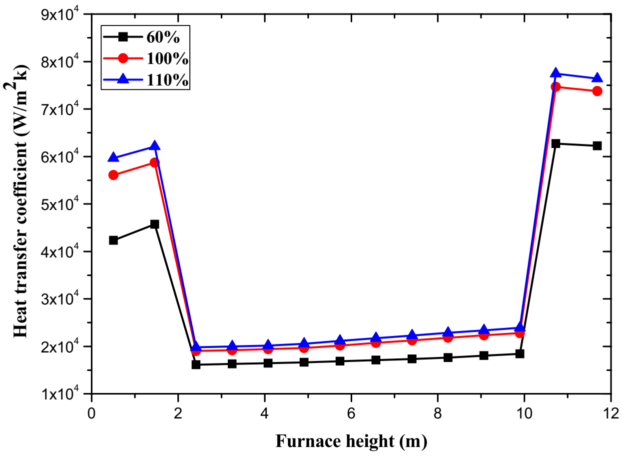

Fig. 11 Heat transfer coefficient distribution along the furnace tube length

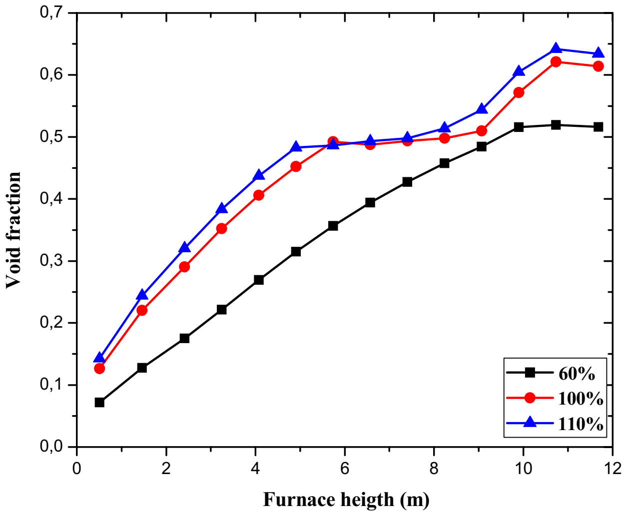

Fig. 12 Void fraction distribution along the furnace tube length

than the vertical part due to the two-phase flow pattern change between vertical and horizontal parts. Thus, it can be understood that heat transfer coefficient can be different through tube length which is due to bubble formation and departure, velocity and flow pattern. We must also note the importance of the correlations used to estimate the convective heat transfer coefficient and the accuracy of the values of the physical properties used in the heat conduction calculation. These two factors significantly affect the calculation.

The Fig. 12 illustrates the void fraction variation along the tube length for the three loads. Initially, at the tube inlet, the void fraction is maintained at the value 0.07, 0.12 and 0.14 at operating loads 60%, 100% and 110% respectively. After that, it increases along the vaporizer tube until reaching the values of 0.518 (60%), 0.614 (100%) and 0.632 (110%) at the end of the tube. As expected, this behavior expresses clearly the tendency of the void fraction to increase along the tubes with the rise of the steam boiler load.

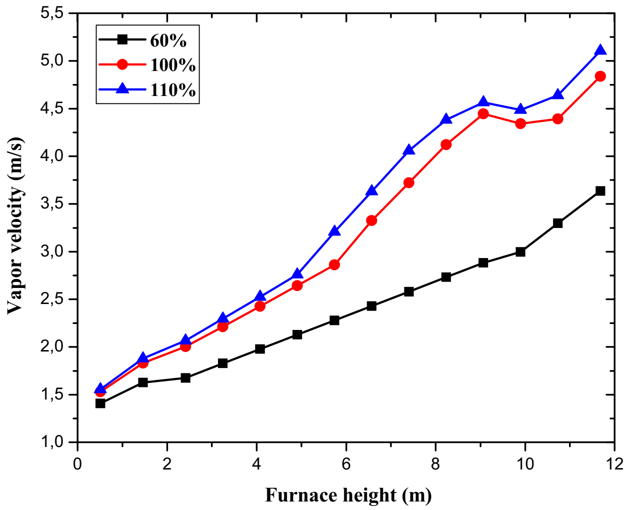

Fig. 13 Vapor velocity distribution along the furnace tube length

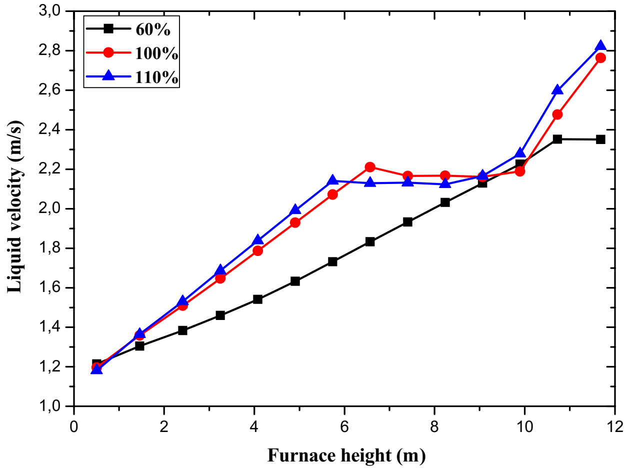

Fig. 14 Liquid velocity distribution along the furnace tube length

The vapor and liquid velocity variations along the vaporizer tube are presented in the Figs. 13 and 14. For the three operating loads, the vapor and liquid velocities increase along the tube reaching 3.63 m/s (60%), 4.83 m/s (100%) and 5.41 m/s (110%) for vapor velocity, and 2.35 m/s (60%), 2.76 m/s (100%) and 2.82 m/s (110%) for liquid velocity at the outlet of the vaporizer tube. It is evident that the vapor velocity is more significant than the liquid velocity, this indicate the magnitude of the mechanical disequilibrium between the vapor and liquid phases. Furthermore, it can be seen from both figures

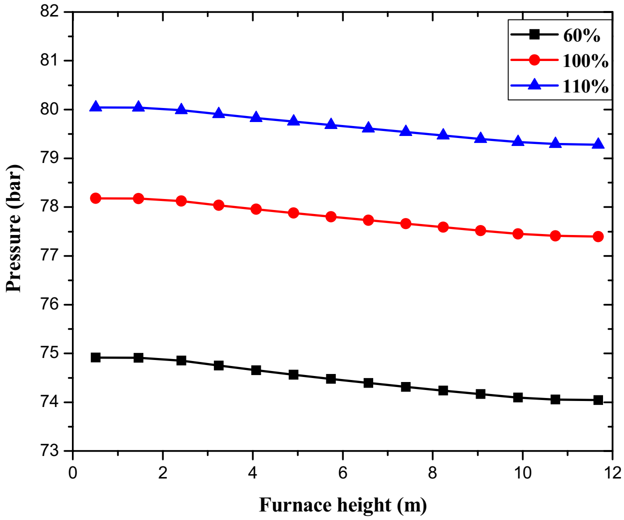

Fig. 15 Pressure distribution along the furnace tube length

that vapor and liquid velocities increase with operating load increasing.

Figure 15 presents the pressure profiles along the vaporizer tube. It shows that the pressure decreases continuously along the tube for the three loads; thus, the total loss of pressure along the furnace vaporizer tube are respectively: 0.83 bars (60%), 0.782 bars (100%) and 0.76 bars (110%). This decrease is caused by gravity, singularities, and effects of the phase change as well as wall friction [35]. In addition to that, the pressure loss decreases with the load increase.

5 Conclusion

In this study, a natural circulation water-tube steam boiler model was developed to predict the boiler behavior and performance at different working loads using RELAP5 system code. Steam boiler parameters have been calculated under three operating loads conditions: 110%, 100% and 60%. The detailed model of the boiler plant is developed according to RELAP5 requirements and all the installation components are included.

Comparison between RELAP5 code results and experimental data under different operating loads is achieved to verify the nodalization quality and to verify the accuracy of the obtained results. The model qualification was carried out in comparison to the corresponding operating data. In spite of the multiple constraints imposed by the complexity of the steam boiler plant, the study outcomes are well consistent with the experimental data with acceptable error margins. In addition, the steady-state is well established at various points of the plant and the set-point values are reached.

A quantitative and qualitative study of the results was carried out to examine the thermal–hydraulic state of the fluid in each component of the steam boiler. The model dealt well with all the thermal–hydraulic phenomena encountered in such facility mainly the natural circulation process and its characteristics, two phase flow, phase separation process in the drum, evaporation and condensation.

The results analysis expresses also that the thermal–hydraulic parameters are influenced by the change of configuration between the vertical and horizontal parts for the vaporizer tube; furthermore, the difference between the liquid and vapor velocities during the natural circulation confirms the existence of the mechanical disequilibrium between the two phases of flow.

Using RELAP5 system code is an efficient approach to predict the performance of the steam boiler under different operating loads and optimize its key operating parameters. In addition, it assures that the thermal–hydraulic parameters are within the design limits especially the temperature of metal are all less than the safety limitations suggesting that the steam boiler can be operated safely under the three working loads and the plant reliability can be ensured.

The pursued goal of the present study was the evaluation and confirmation of the RELAP5 code capabilities for simulation of the conventional thermal–hydraulic installations such as steam boilers and to reproduce the main thermal–hydraulic phenomenon that may occur. This work has allowed us to develop a basic model that can simulate not only the steam boiler normal operation but also some hypothetical accidents that may occur during its lifetime.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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