Chapter

Numerical Simulation of the Accidental Transient of an Industrial Steam Boiler

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Abstract

Numerical simulation allows a better understanding of thermal-hydraulic phenomena that can take place in thermal installations. It is a capital contribution, especially in accident situations. The code RELAP5/Mod3.2 makes it possible to predict the thermal-hydraulic behavior of these installations during the normal and accidental operations. The present chapter focuses on accidental transient modeling and simulation of an industrial steam boiler by the code RELAP5/Mod3.2. This steam boiler is radiant type, high power, natural circulation, and a single drum. The model of the boiler developed for the RELAP5/Mod3.2 code encompasses the entire installation. The control loop of the water level in the steam drum and the superheated steam temperature are also included in the model. The qualification process of the steam boiler model is based on the steam boiler operation data under steady-state operating conditions. The comparative study shows that the theoretical results of the code RELAP5 are in good agreement with the operating data of the installation. To evaluate the behavior and response of the boiler in accident situations, the loss of feedwater following pump power loss, with and without protective operations, was simulated.

Keywords: industrial steam boiler, natural circulation, safety, modeling and simulation, RELAP5/Mod3.2, accidental transient

1. Introduction

Electricity production largely depends on the production of steam using coal, gas, or nuclear fission of uranium as heat sources. To produce steam, it is necessary to heat the water to its boiling point and then to provide a sufficient amount of heat to change the boiling water into steam. Steam production and utilization techniques are therefore important aspects of engineering technology. The steam generator is one of the means used to produce steam. A steam boiler plays an important role in all types of industries; it is one of the key components of a thermal installation. The main function of the steam boiler is to produce steam for the purpose of using it for industrial reasons such as the production of electrical energy, petro-chemistry, district heating, and others [1]. In general, the steam boilers can be classified in two categories: water-tube and fire-tube steam boilers. The choice of the type of industrial steam boiler to be selected can be made according to several criteria, the main one being the thermal power to be supplied or its equivalent in production of steam.

In the steam boiler, several problems can occur during its service because it works in severe conditions (high pressure, high temperature, corrosive environment, and continuous operation). These problems have an influence on steam boiler operation and sometimes lead to serious consequences such as explosions. Indeed, accidental transient was already observed during normal operation of the installation [2]; the most important and the most frequent are loss of feedwater, loss of flow, pipeline ruptures, loss of electrical power, equipment failures, and others. Early detection of such faults under operation is of great importance. Therefore, it is very necessary to perform an accident analysis to evaluate causes and make an assessment of the accidents' consequences [3]. Finally, it is important to consider the safety aspects and analysis of the steam boiler to guarantee the reliability and stability.

Steam boiler is a complex equipment considering the nonlinear, phase change, and inverse response behavior (shrink and swell). However, the operating conditions of the steam boiler are very difficult to control because all the parameters are interrelated. In addition, the steam boiler has very high manufacturing, operating, and maintenance cost. Hence, it is very difficult to take measurement and carry out tests directly on steam boiler. However, modeling and simulation are also effective tools for safety assessment and prediction of installation behavior of real process under transient conditions. The usefulness of numerical simulation tools is mainly based on the development of numerical methods, the progress of programming, and the provision of powerful computing resources [4].

The power plants' safety is largely based on simulation [5]. Nowadays, the best-estimate nuclear system codes such as TRAC [6], RETRAN [7], RELAP5 [8, 12], ATHLET [9], CATHARE [10], and APROS [11] are widely used to investigate the thermal-hydraulic characteristics of nuclear power plants either during steady-state operation or accidental transients and simulate the overall behavior of the installation (pumps, piping, heat exchangers, tanks, valves, control loops, etc.).

They are mainly produced to simulate the behavior of nuclear installations, but they can also be used to study the normal and accidental operation of conventional thermal, industrial, and solar installations [13, 14, 1, 2].

RELAP5 code used to carry out the present study is a thermal-hydraulic analysis system code of a realistic estimation level (best estimate). It is used to simulate the thermal-hydraulic transient of light water systems during postulated accidents [15]. RELAP5 is widely used in nuclear safety studies; its scope extends to energy systems using water and its vapor. Research work in this direction is very limited to the nuclear field. Extrapolation of the code scope is possible for the thermal-hydraulic behavior study of an industrial boiler [1, 2, 16].

In this chapter, realistic simulation of the global behavior of an industrial natural circulation steam boiler during normal and accidental operation is performed using RELAP5/Mod3.2 system code with a thermal-hydraulic performance analysis of the main equipment of the installation. A better understanding of the physical phenomena occurring during all phases of a hypothetical accident is necessary for the safety of an installation. The accidental transient simulated in this chapter is the loss of feedwater (pump stop) with and without protective operations. The chapter is divided into the following sections:

- Presentation of the steam boiler
- The RELAP5/Mod3.2 computer code
- The simulation application by the RELAP5 code

- The transient simulation of the steam boiler
- Conclusion

2. Steam boiler

Steam is used in energy production and in many industrial processes. Its production and utilization techniques are therefore important aspects of engineering technology. Among the means of producing steam, there are steam generators, which are vital to power and processing plants.

2.1 Steam boiler history

The use of two-phase systems accompanied by a phase change to transform thermal energy into mechanical energy is old. It dates back to the first century with the invention of the aeolipile by the Greek mathematician Héron d'Alexandrie [17]. However, no practical system was built until the Italian architect and inventor Giovanni Branca designed a boiler. But, it is really only from the end of the seventeenth century that engineers developed modern steam machines. The first real steam machine was built by English engineer Thomas Savery in 1698; this machine was used for pumping water. The James Watt boiler, built in 1785, who was one of the first engineers to achieve the thermodynamic properties of steam, used the safety valve and valves to control the flow of water and steam in its boilers [18]. At the beginning of the nineteenth century, British engineer Richard Trevithick and American inventor Oliver Evans developed machines without condenser using high-pressure steam. Trevithick used this model steam engine to equip the first railway locomotive. Trevithick and Evans built road vehicles powered by steam [18]. The French engineer Marc Seguin (1781–1875) developed a fire-tube boiler, which in 1827 equipped George Stephenson's famous "Rocket" locomotive. The first improvement in Evans' boiler was the "Lancashire" fire-tube boiler patented in 1845 by British engineer William Fairbairn, in which the flue gases circulated through tubes inserted in the water tank, increasing the area through which heat could be transmitted. Fire-tube boilers, however, had limited capacity and pressure and sometimes presented a risk of explosion [17]. The first boiler with water tubes (**Figure 1**) patented in

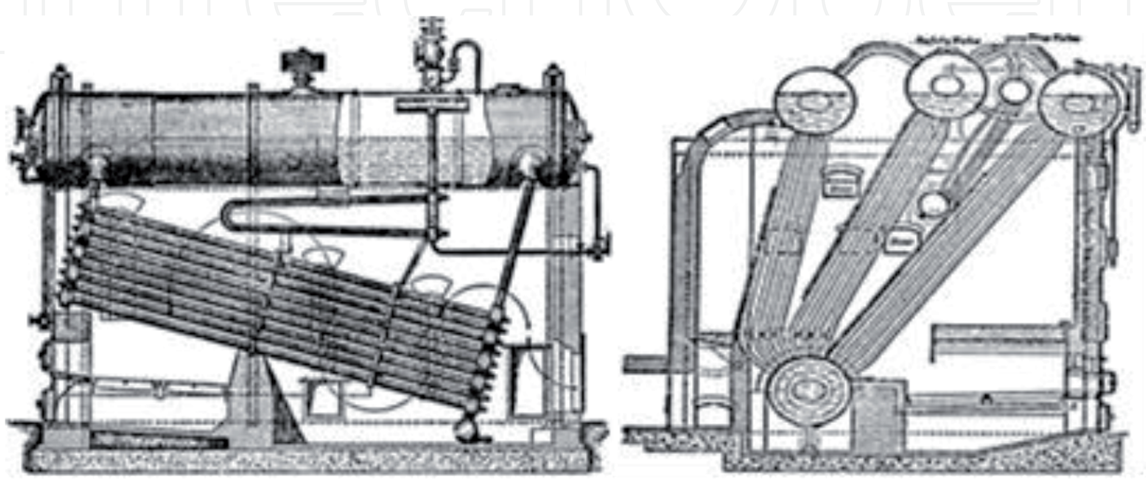


Figure 1.
First boilers with water tubes (Babcock and Wilcox).

1867 by American inventors George Herman Babcock and Stephen Wilcox allowed a higher pressure than that of the fire-tube boiler [19]. In this boiler, the water passed through tubes heated from the outside by the combustion gases, and the steam was collected in a top drum. In the twentieth century, the water-tube boiler found wide applications due to advances such as high-temperature steel alloys and modern welding techniques, which made the water-tube boiler the standard boiler type for all high-capacity boilers.

2.2 Steam boiler classification

Steam boilers can be classified according to various parameters such as design (fire-tube or water-tube), depending on the support, circulation method of water, steam and water/steam mixture (natural circulation, forced circulation), and thermal power. These are fuel-steam generators; they consist of two separate compartments, one in which the fuel burns and the other in which the water circulates. But generally, they are classified in two categories: water-tube and fire-tube steam boilers.

2.2.1 Fire-tube steam boiler

In this type of boiler, the flue gas passes inside submerged tubes in the water (**Figure 2**) [20]. These steam generators are widely used in industrial and commercial facilities, especially in the locomotives and marine applications. Modern fire-tube steam boiler can produce steam pressure up to 25 bars (low and medium pressure) and a flow rate of 1–25 t/h [19]. They can use natural gas, oil, or solid fuel.

The fire-tube steam boiler consists of a cylindrical tank, which contains tubes inside. These tubes collect the hot gases at the exit of the burner. Hot gases, accumulated in a first pass at the back of the steam boiler, are carried by a group of tubes submerged in water to a second pass at the front of the boiler. A second group of submerged tubes take the combustion gases to a third pass at the rear of the steam boiler; this third pass opens on the chimney for the evacuation of fumes to the outside. The heat transfer between the tubes and the combustion gases is mainly done by the convection mode. A typical example of this boiler is illustrated by **Figure 3**.

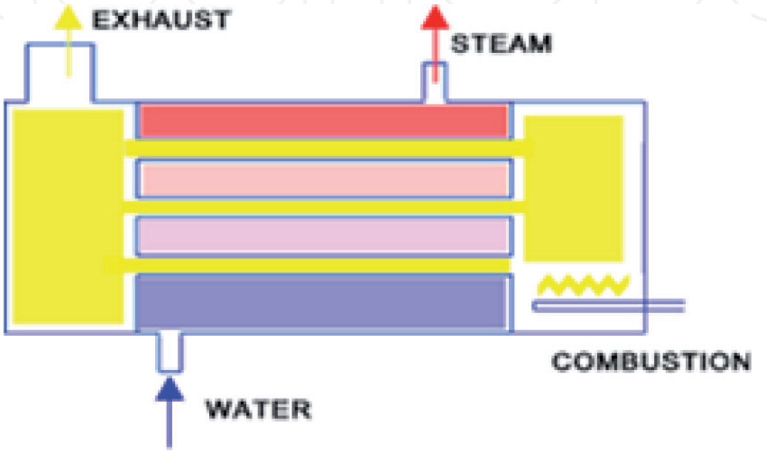


Figure 2.
Principle of fire-tube steam generator.

Figure 3.
Typical fire-tube steam boiler.

2.2.2 Water-tube steam boiler

It is a type of steam generator in which water circulates in tubes that are externally heated by flue gases (**Figure 4**) [19, 20]. They represent the vast majority of steam generators in service.

These steam boilers are used in industrial and power plants to produce high steam pressure. They use gas, oil, or solid combustible as fuel [19]. A typical water-tube steam boiler is illustrated by **Figure 5**. Generally, water-tube steam boilers have two or more tanks, the upper tank called collecting tank (drum) and lower tank called distributor tank. The hot gases produced by the burner are directly in contact with the evaporating tubes; inside of these, vaporization occurs. The steam thus generated is collected in the drum, and the excess water is returned to the bottom tank by non-heated pipes (downcomer). The heat transfer between the tubes and the combustion gases is mainly done by radiation. The flue gases can also be used in the preheating of combustion air and the feedwater.

The performance comparison of the two types of steam boiler is presented in **Table 1**.

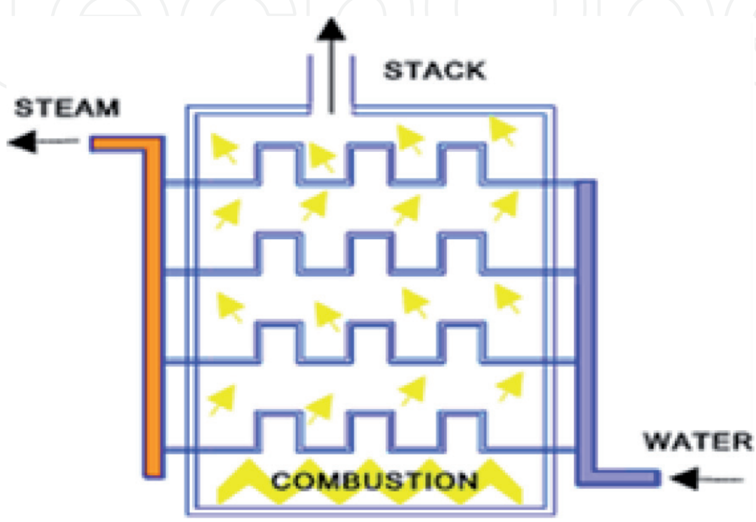


Figure 4.
Principle of water-tube steam boiler.

Figure 5.
Typical water-tube steam boiler.

Properties	Fire-tube steam boiler	Water-tube steam boiler
Start-up (equivalent power)	Slow (large volume of water to heat)	Quick
Adaptation to regime changes	Mediocre (significant inertia)	Good
Heating surface	Medium	High
Security	Mediocre	Good
Congestion	Low	Strong
Price	Limit	High
Usual applications		
• Power • Flow rate • Max working pressure	• Moderately high • 1.5–25 t/h • 10–20 bars	• Important • Higher • 70–225 bars

Table 1.
Comparison of the two types of steam boiler.

2.3 Water circulation mode

The role of the water circulation or the emulsion of water and steam in the steam boiler tubes is to ensure, on the one hand, the correct cooling of the tubes located in the hottest areas or exposed to radiation and that receives at this part the maximum heat flow and, on the other hand, to ensure the generation of saturated steam, that is to say, the passage of the heated fluid from the water state to the water and vapor emulsion state. There are two main types of circulation, natural circulation and forced circulation.

2.3.1 Natural circulation

It establishes itself in the circuits of the steam boiler. It is ensured by the difference of weight between two columns of fluids, one containing only water and the other a mixture of water and steam. The effect of natural circulation decreases when approaching the critical pressure of 221 bars; the practical limit of the use of natural circulation is 180 bars [21]. In steam boilers with natural circulation, the boiling is done in nucleated form, which guarantees a good cooling of the vaporizing tubes [20, 21]. When the power decreases, the void fraction varies relatively little, and consequently the flow in circulation decreases much less quickly than the steam flow of the steam boiler; this guarantees the cooling of the tubes. Natural circulation is therefore relatively more active at low power. It should be noted that the natural circulation is better when the pressure is low and the heating part is located at the bottom of the furnace.

2.3.2 Forced circulation

The circulation of water in such boiler is provided by the feed pumps [21]. This circulation allows great liberty in circuit design, since circulation is always assured. In addition, the diameter of the tubes may be smaller than in natural circulation boilers. In forced circulation boilers, the water vaporized in totality by the unstable film evaporation regime and then by stable film is established necessarily in the final parts of the circuit; it must then be controlled that the speed of the emulsion is sufficient to ensure the cooling of the tube. Forced circulation boiler can be used for all subcritical and supercritical pressures.

2.4 Different components of a steam boiler

We distinguish mainly:

- Drums
- Combustion chamber
- Heat exchangers (economizer, superheater, desuperheater)
- Integrated control
- Valves and flappers
- Feedwater and steam piping
- Pumps

3. Modeling and simulation using RELAP5/Mod3.2

This section describes the modeling and simulation of an industrial steam boiler using RELAP5/Mod3.2 in the steady-state and accidental transients.

3.1 Presentation of the steam boiler used for this study

The steam boiler used in this chapter is a water-tube, radiant type, and high power, with natural circulation from an ABB ALSTOM brand. It is installed in the natural gas liquefaction (NGL) complex which is operated by SONATRACH Company; is located at 5 km east side of Skikda, Algeria; and 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].

This boiler operates at high heat flux density to produce 374 t/h of superheated steam at 73 bars and 487°C with a design thermal efficiency around 92% [2, 22]. It is composed of three main parts: the steam generator, the superheated steam line, and the feedwater line. A schematic representation of the steam boiler installation is illustrated by **Figure 6** [1, 2].

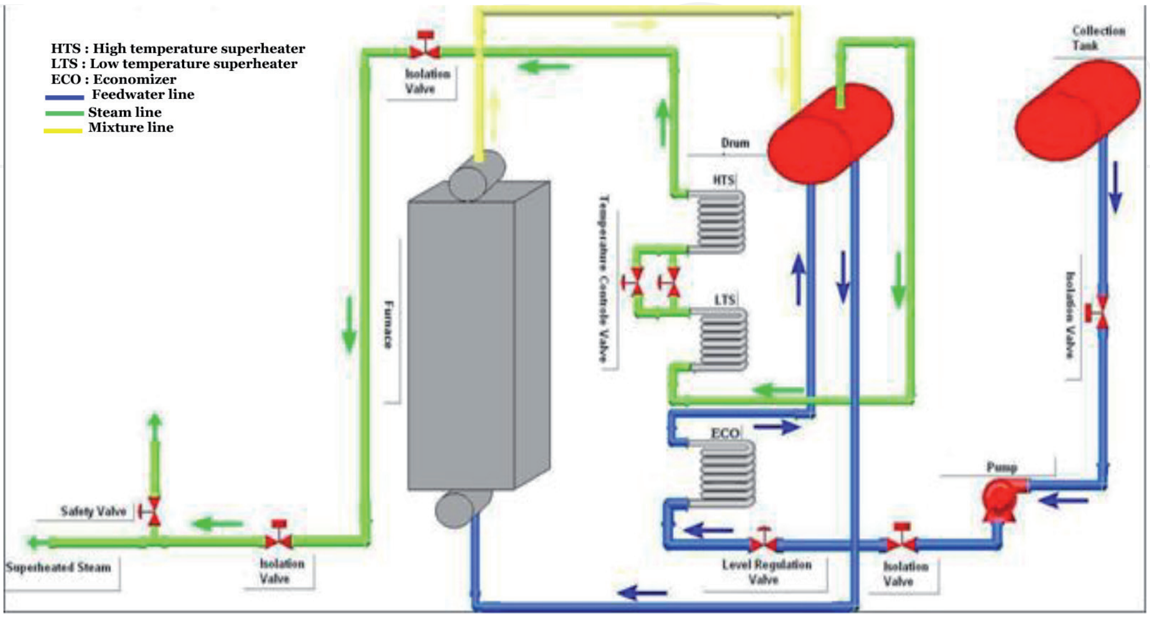


Figure 6.
Steam boiler installation [1].

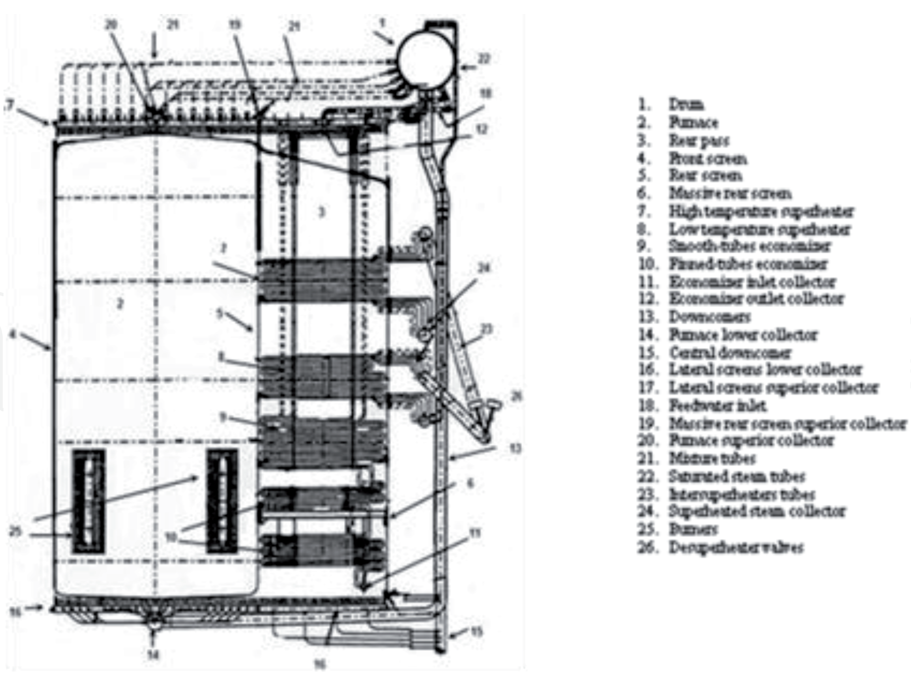


Figure 7.
Longitudinal section of the steam generator [2].

The entire plant can be subdivided into three main parts, the feedwater line, which refers to the saturated liquid phase, the steam generator, and, finally, the main steam line and its transformations. The steam generator consists of one drum and two main parts; the first concerns the combustion chamber, and the second

Technical parameters	Unit	Values
Steam flow rate	t/h	374
Drum pressure	Bar	76.9
Feedwater inlet temperature	°C	118
Outlet furnace gas temperature	°C	1147
Airflow rate	Nm^3/h	344,800
Natural gas flow rate	Nm^3/h	45,699
Air excess in the furnace	%	1.3
Efficiency	%	92
Estimated heat flux densities		
Furnace	kW/m^2	162
Economizers	kW/m^2	34.35
Primary superheater (HTS)	kW/m^2	60.54
Secondary superheater (LTS)	kW/m^2	34.97

Table 2.
Steam boiler operating parameters.

is the rear pass materialized by the water walls that form the evaporating tubes. The rear pass receives the superheaters at high and low temperatures at the top and the economizers below. The steam boiler is designed to operate by combination of automatic and manual operation. The main feedwater line includes the collection tank, two feed pumps, tree economizers, control and isolation valves, and feed piping. The main steam line is constituted by high and low superheaters, steam piping, pipeline of desuperheater, and control and safety valves. The steam generator shown in **Figure 7** [2] and the main operating characteristics of the steam boiler are given in **Table 2**.

The heat transfer between the wall of the tubes and the combustion gases is generally done by two modes, radiative and convective [23]; in radiant steam boilers, as the name suggests, it receives almost the heat by radiation: convection and conduction represent only 5% [19, 20]. The heat received by the water walls is conducted through the membranes and walls of the tubes and transferred by forced convection to nucleate boiling to the water/vapor mixture in the vaporizer tubes.

The installation contains two control loops: water level control in the drum and superheated steam temperature control, in order to maintain the stable operation of the steam boiler. A detailed description of the steam boiler plant can be found in Ref. [1, 2].

3.2 Adopted code and nodalization

3.2.1 RELAP5/Mod3.2 code presentation

The Reactor Excursion and Leak Analysis Program (RELAP5) is a best-estimate nuclear system code; it was developed at Idaho National Engineering Laboratory (INEL) at the request of the US Nuclear Regulatory Commission (NRC) [15]. It is mainly used for the transients' analysis of light-water reactor (LWR); however, the generalization of the RELAP5 code allowed its application to the nuclear and nonnuclear fields [1, 4, 11]. It has been designed to simulate the thermal-hydraulic behavior of installations during accidental or incidental transients. RELAP5 is based on a nonhomogeneous and nonequilibrium hydrodynamic model for the two-phase system. It solves the unstable and one-dimensional equation of mass, energy, and momentum for each phase using the semi-implicit finite difference numerical method [15, 24].

The series of RELAP codes are started by Reactor Leak and Power Safety Excursion (RELAPSE). Previous versions of the RELAP code are RELAP2 and RELAP3, where the name RELAPSE has been changed to RELAP. All these versions are based on equilibrium homogeneous model for two-phase flow [15]. The development of a model of nonhomogeneous nonequilibrium was undertaken for RELAP4. In 1976, the last version (RELAP4/MOD7) of this series of codes has been released. It is clear that a complete rewrite of the code was required to effectively accomplish this goal. The result of this effort was the beginning of the RELAP5 project [15]. RELAP5/MOD3 is the third major release of the RELAP5 thermal-hydraulic system code which was realized in 1985. It is written in FORTRAN 77 for a variety of 64-bit and 32-bit computers. The latest version of the RELAP5 (RELAP-3D) code simulates three-dimensional thermal-hydraulic and neutron phenomena.

RELAP5 is designed in a modular way, using an ordered structure. The procedures and the models are separated into sub-programs and constitute the basis of thermal, hydraulic, and neutronic treatment. An option introduced makes it possible to perform the various calculations related to the steady state, by using the following algorithms:

- Algorithm for kinetics
- Algorithm for the control system
- Algorithm for the hydrodynamic transient
- Algorithm for the thermal transient

Parameters such as pressure, flow rates, and densities would adjust quickly, but the thermal effects evolve more slowly. The accelerated transient technique is therefore used to reduce the transient computation time required to reach steady state. The transient calculation is characterized by the temporal variation of one or more variables related to the studied problem. Usually, the transient regime must be preceded by a well-established steady state in which the initial conditions of the simulated accident are completed. The introduction of the initial values is necessary for the execution of a problem either in the steady state or in the transient state. These values are provided by the user in the input for each component [15].

The RELAP5/MOD3.2 code includes many generic component models for the modeling of various systems and physical phenomena such as pipe, pump, turbines, separators, valves, accumulator, point kinetics of reactors, heat structure, control system component, etc. [25]. In addition, other special process models are introduced for the different form losses, flows in pipes with variable surfaces, branching and choked flow, and others. The programming of the various hydrodynamic calculations is based on a concept of volumes and junctions. System simulation consists to subdivide the plant into components connected by flow junctions. The main component models that are introduced in the RELAP5/MOD3.2 code are grouped in **Table 3**.

The code allows the calculation of the heat transfer through the solid walls, delimiting the hydrodynamic volume. Heat structures are solid elements that generate heat or not, put in contact with the fluid volume. Each heat structure is defined by the indices of the left and right control volumes, the solid volume, its thickness, and the type of the material. The heat transfer modeling of metal structures usually

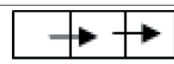
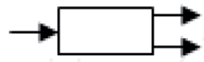
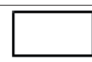
Component	Label	Schematic	Definition and scope
Single volume	SNGLVOL		Represents a fluid volume in the system
Pipe or annulus	PIPE		Represents a pipe in the system
	ANNULUS		Special pipe, used to simulate an annular flow
Branch	BRANCH		Represents a stream pipe flow juncture
	SEPARATR		Used to simulate the separator in a steam boiler
	TURBINE		Used to simulate a steam turbine
Single junction	SNGLJN		Designed to connect one component to another
Time-dependent volume	TMDPVOL		Imposes the thermodynamic conditions at the system boundary
Time-dependent junction	TMDPJUN		Connect some components to another and imposes the circulation flow
Valve	VALVE		A special junction used to simulate an action and the presence of different valves
Pump	PUMP		Simulates the centrifuge pump
Accumulator	ACCUM		Simulates a PWR accumulator

Table 3.
Main thermal-hydraulic components of the RELAP5/Mod3.2 code [25].

includes fuel rods and plates (source of electrical heat or nuclear), heat transfer through the tubes of the steam generator, and the heat transfer to the walls of pipes and tanks in the case of a reactor. The temperature distribution in the heat structures is represented by one-dimensional heat conduction in spherical, rectangular, or cylindrical coordinates. The thermal conductivity and the heat capacity can be simulated by a series of tabulated values according to the temperature or a given function. The integral form of the heat conduction equation is given by expression (1), and finite differences are used for solving this equation [26].

$$\iiint_v \rho C_p(T,\bar{x}) \frac{\partial T}{\partial t}(\bar{x},t)dV = \iint_s k(T,\bar{x})\, \bar{\nabla} T(\bar{x},t) \cdot d\bar{s} + \iiint_v S(\bar{x},t)dV \qquad (1)$$

The heat transfer model of the RELAP5 code divides the thermal transfer between the two phases—liquid and vapor (**Figure 8**). The total heat flux Q takes the following expression [26]:

$$Q = h_g(T_w - T_{refg}) + h_f(T_w - T_{reff}) \qquad (2)$$

where h_g: coefficient of heat transfer to steam; h_f: coefficient of heat transfer to liquid; T_w: wall temperature; T_{refg}: vapor reference temperature; T_{reff}: liquid reference temperature.

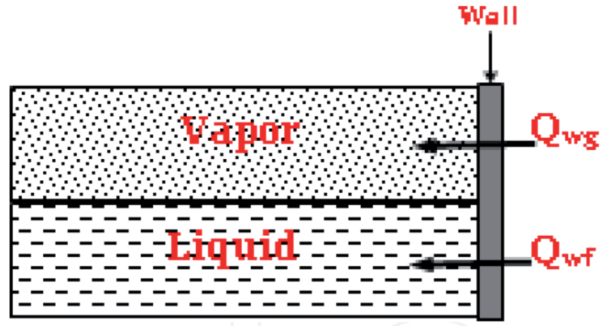


Figure 8.
Heat transfer process.

Figure 9.
Discretization scheme.

The reference temperature can be the local temperature of liquid and vapor or the saturation temperature, all depending on the heat transfer correlation used. The wall temperature is calculated implicitly, and the reference temperature can be variable during the calculation. Wall-fluid heat transfer is subdivided into three regimes: condensation, convection, and boiling [26].

Figure 9 illustrates the position of the different nodes (mesh points) for the temperatures' calculation. Each interval may contain different spacing between nodes, different materials, or both. The interval between nodes takes an axial direction for a rectangular structure and a radial direction for a cylindrical or spherical structure. Heat sources can be simulated by the kinetics of the reactor (nuclear source), a series of tabular values as a function of time, or by a control variable.

The code permits the introduction of different boundary conditions such as isolation conditions of tubes, surface temperature tables as a function of time, and atmospheric losses. These boundary conditions can be simulated in different ways: imposed heat flow, imposed temperature, and convection coefficient. A heat transfer correlation series is used to calculate the heat transfer between the circulating fluid and the metal structures connected to the hydrodynamic volumes. This series covers the different modes of heat transfer, convection, radiation, nucleate boiling, transient boiling, and boiling by film.

Boiling curves are used to select correlations of heat transfer. Modeled heat transfer regimes are classified as nucleate boiling, critical heat flow point (CHF), and dispersed flow regime. The heat transfer of condensation is also modeled. The pre-boiling regimes concern the liquid monophasic convection, subcooled nucleate boiling, and nucleate boiling at saturation [15].

3.2.2 Steam boiler nodalization

Knowledge of all the components and parts of the installation as well as all the physical phenomena that may occur in the system is essential for the modeling of any thermal installation. Preparing data to access this type of work using the RELAP5 code requires considerable effort because of the large amount of

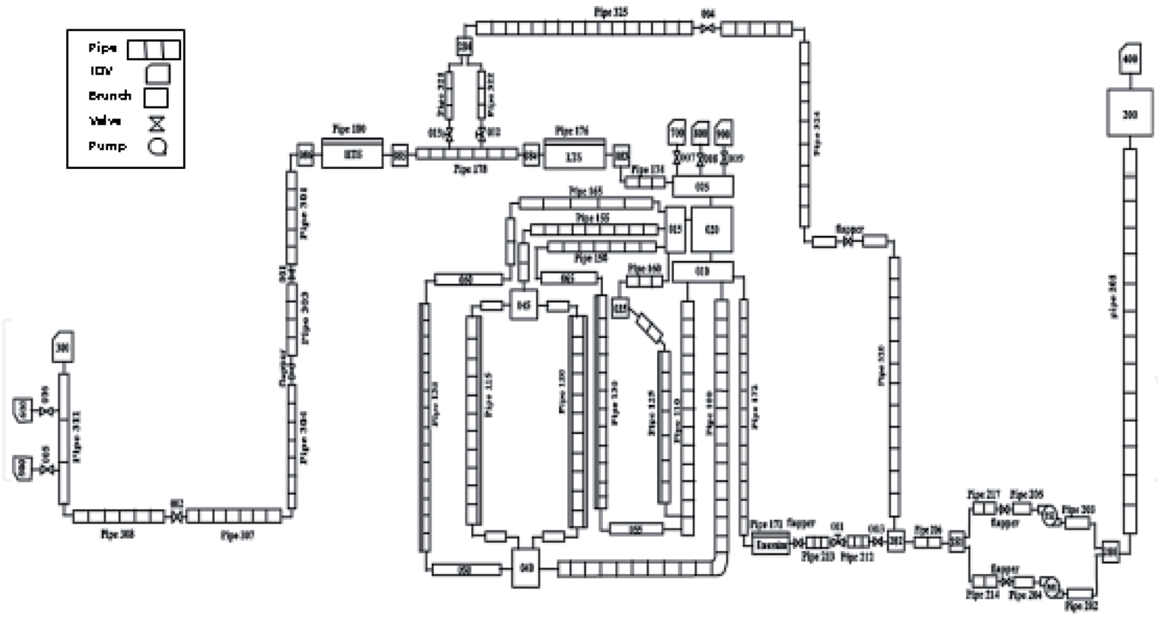


Figure 10.
Nodalization of the steam boiler installation.

information required for the entire installation and its associated components. The information and data of the modeling of the steam boiler plant were obtained from the installation documentation and staff [22], that is, the RELAP5 steam boiler model is based on geometrical and technical data.

The philosophy of using the RELAP5 code is to subdivide the hydrodynamic system into control volumes connected by flow junctions. The thermal behavior of the metal wall of the boiler tubes, such as heat transfer with the fluid, is modeled by heat structures that are connected to vaporizer tubes and heat exchangers. The heat densities between the combustion gases and the external surfaces of the vaporizer tubes are calculated from the energy balance performed on the fumes at each exchanger.

The thermal-hydraulic conditions at the inlet and outlet of the installation represent the condensed feedwater that enters the collection tank and the superheated steam flowing to the turbine. Regulation plays a very important role in the operation of the steam boiler; the RELAP5 code includes the possibility to model the regulation system by components specific to the code. The installation of the entire steam boiler is modeled in 582 control volumes, 589 junctions, and 142 heat structures. The thermodynamic conditions at the system boundaries are imposed by "time-dependent volumes" component **Figure 10** shows the nodalization diagram of the entire installation. More details on the steam boiler nodalization are given in Ref. [1, 2]. The modeling of the steam boiler using the RELAP5 code will be followed by a qualification at the steady-state level.

3.3 Validation at steady-state level

Numerical simulation allows a better understanding of thermal-hydraulic phenomena that could take place in industrial installations; they are of a capital contribution especially in accident situations. The RELAP5 code allows the prediction of the thermal-hydraulic behavior and response of the steam boiler during normal and accidental operations. Prior to the transient accident analysis, it is essential to check the establishment of the steady state in different points of the steam boiler installation. The steady state is reached after running the RELAP5/Mod3.2 code for 5000 seconds in our case study. To demonstrate the establishment of the steady

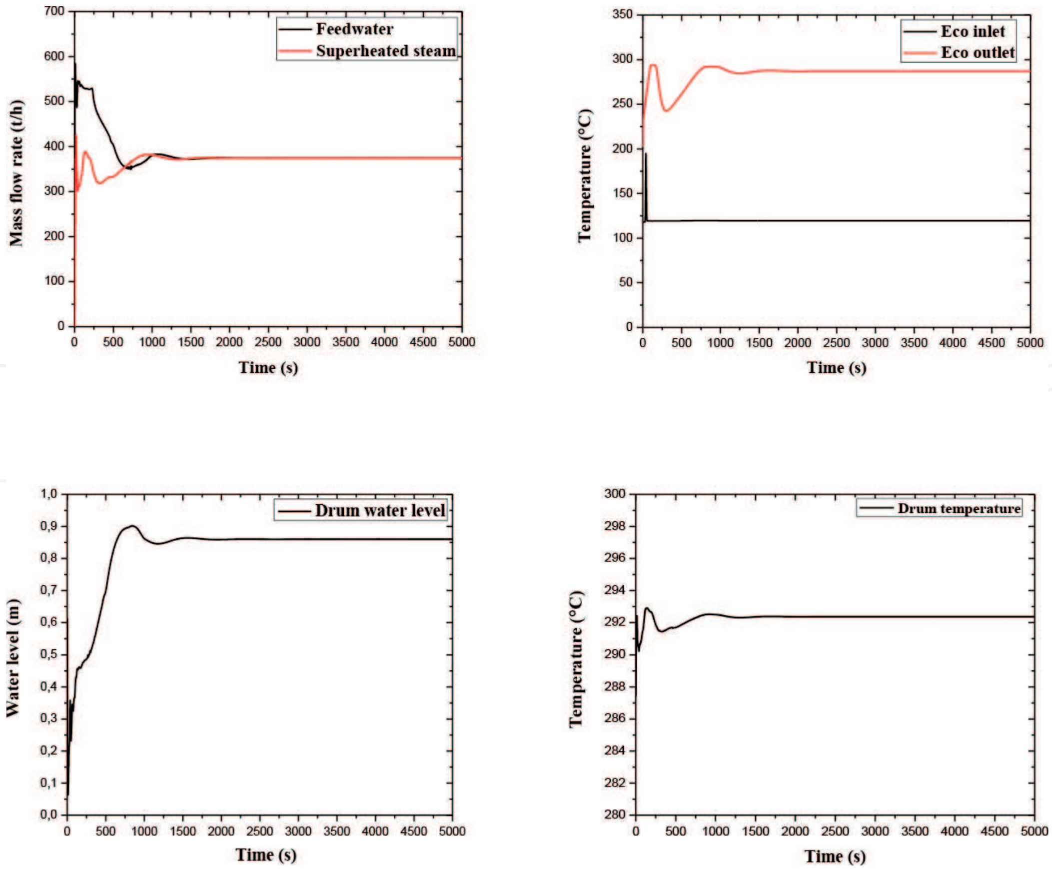


Figure 11.
Main steam boiler parameters during steady state.

Boiler parameters	Units	Experimental data	Simulation data
Feedwater flow rate	t/h	374	374.121
Steam flow rate	t/h	374	374.357
Desuperheater flow rate	t/h	25	26.043
Inlet economizer temperature	°C	118	119.0
Outlet economizer temperature	°C	287	287.030
Outlet drum steam temperature	°C	292	292.368
Inlet LTS temperature	°C	292	292.316
Outlet LTS temperature	°C	370	370.848
Inlet HTS temperature	°C	322	320.141
Outlet HTS temperature	°C	487	487.338
Drum water level	mm	860	860.003
Pressure at collection tank	Bar	1.89	1.89
Drum pressure	Bar	76.9	77.2
Inlet steam generator pressure	Bar	82	78.2
Outlet steam generator pressure	Bar	73	73.199
Outlet pump pressure	Bar	91.93	94.150

Table 4.
Comparison between operating and calculated data at steady state.

state, we selected some steam boiler operating parameters (**Figure 11**). The analysis of the curves representing the evolution of these parameters showed that the regime is stationary and well established, and the set-point values of the regulation system were reached.

The qualification of the steam boiler RELAP5 model is based on available operating data, and it aims to verify that the steady state is well reproduced. In order to validate the plant nodalization under steady-state condition, the simulation results are compared with the experimental data; it provides precious information on the quality of the nodalization, the selection of the appropriate code options, and the appropriate choice of the boundary and initial conditions (1). The comparison between the RELAP5/Mod3.2 results and operating data at steady state is summarized in **Table 4**. As it could be seen, the simulation results are in good agreement with the operating data of the steam boiler, proving the adequacy of the model and expressing the capacity and reliability of the RELAP5/Mod3.2 code in simulating thermal-hydraulic behavior of industrial installations. At this level, it should be noted that the present model could potentially be used for further transient analysis.

3.4 Transient calculation

For a steam boiler, loss of feedwater is the most severe incident that can occur and that may potentially end with serious consequences because water flow rate decreases suddenly leading to a decrease in drum water level and the walls of the tubes are overheated. Various factors can produce this accident; it can be caused by pump power loss, failure of the feedwater pump, ruptures and leakages from pipes located in the main feedwater line, feedwater control valve closing, or failure of the water level regulation [27].

In this chapter, the numerical simulation of the steam boiler thermal-hydraulic behavior and response during loss of feedwater accident caused by the pump power loss is discussed. The transient was performed including protected and unprotected scenarios. In the first one (protected scenario), it is assumed that all control systems are functioning properly to mitigate the sequences of the accident; in the second one (unprotected scenario), it is assumed that there is a failure in the security and control system. Prior to the accident, the steam boiler was operating under steady-state condition. The accidental transient is initiated when the feedwater pump costs down accidentally leading to a sudden decrease in feedwater flow rate. The burners' shutdown is actuated immediately following the triggering of the pump stopping alarm signal. **Table 5** groups the main events describing the accidental scenario as a function of time.

Occurrence instants	Sequence	
	Protected scenario	Unprotected scenario
−500 to 0 seconds	Steady-state regime	X
At 0.0 seconds	Feedwater pump costs down	X
After 0.25 seconds	Alarm signal generation	
At 5 seconds	Burners' shutdown	
At 100 seconds	Closing the steam isolation valve	
At 1000 seconds	End of transient	

Table 5.
Main accidental sequences of the transient.

3.5 Transient analysis

To illustrate the behavior and response of the steam boiler during this transient, the main parameters are presented in curves showing their evolution with time. The curves from **Figures 10–15** show the behavior of each selected parameter even during protected or unprotected scenarios. The transient simulation is preceded by a steady-state period equal to 3000 seconds (this time corresponding to the stability of the entire installation at nominal steam boiler load) with a time step size equal to 10^{-3} seconds.

The temporal variation of feedwater and superheated steam mass flow rate for both scenarios are illustrated by **Figure 12**. Before the accident, the two flow rates are at the same initial value of 374 t/h. After the accident occurrence, the feedwater flow rate decreases instantly, and the superheated steam flow rate vanishes gradually for 90 seconds after the burner shuts down, due to the stopping of steam generation inside the vaporizer tubes. In the second scenario (unprotected), an increase in superheated steam flow rate is observed up to 513.78 t/h which is due to the continuous water vaporization in the vaporizing tubes. At the instant t equals 318 seconds, the flow rate begins to decrease until there is more water in the tubes to vaporize.

Figure 13 shows the time variation of the pressure in the drum. In the first scenario, following the accident and burners' shutdown, the pressure drops rapidly until 72.44 bars at 58 seconds. From this instant, it continues to decrease but more slowly until the end of the transient. This is due to the cooling of the boiler by the ventilation air. In the second case (unprotected), after the accident, the pressure increases to a value of 81.58 bars resulting from the vaporization. Then at time 313 seconds, the pressure starts to drop, and when it reaches 72.69 bars, it stabilizes at that value until the end of transient.

The water level in the steam boiler is a key parameter since it indicates the mass of water in the boiler. So, for safety reasons it must be kept in a limited range [28]. The behavior and response of the water level in the drum are shown in **Figure 14**. It is maintained before the accident at the value of 860 mm (set-point). For the case of the protected scenario, and after stopping the feedwater pump, the level drops suddenly to the value of 359 mm due to the decrease in pressure (**Figure 13**) which generates an intense vaporization of water in the drum. Then it continues to decrease but more slowly until reaching the value of 206 mm at the end of the transient. In the unprotected case, the level decreases slowly and almost linearly contrary to the first case, due to the presence of vapor bubbles in the drum.

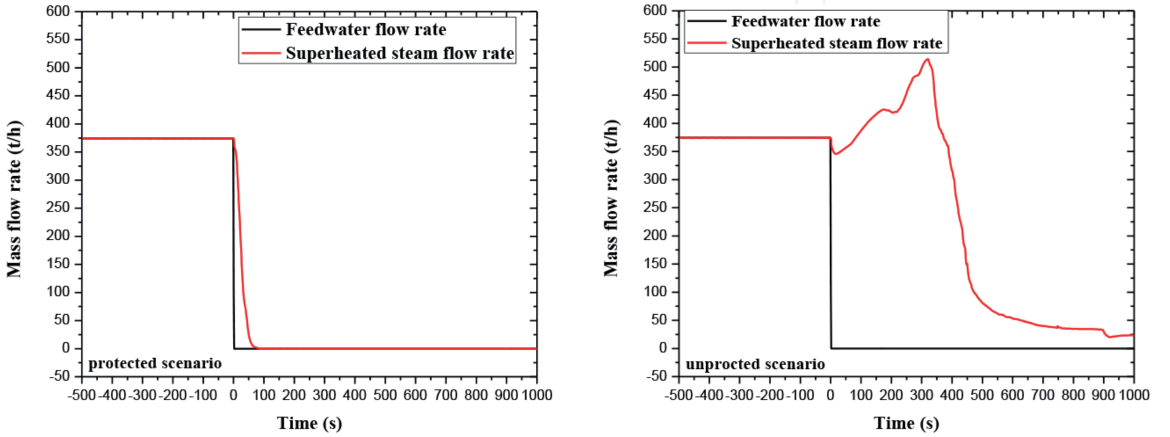


Figure 12.
Time variation of feedwater and steam flow rates.

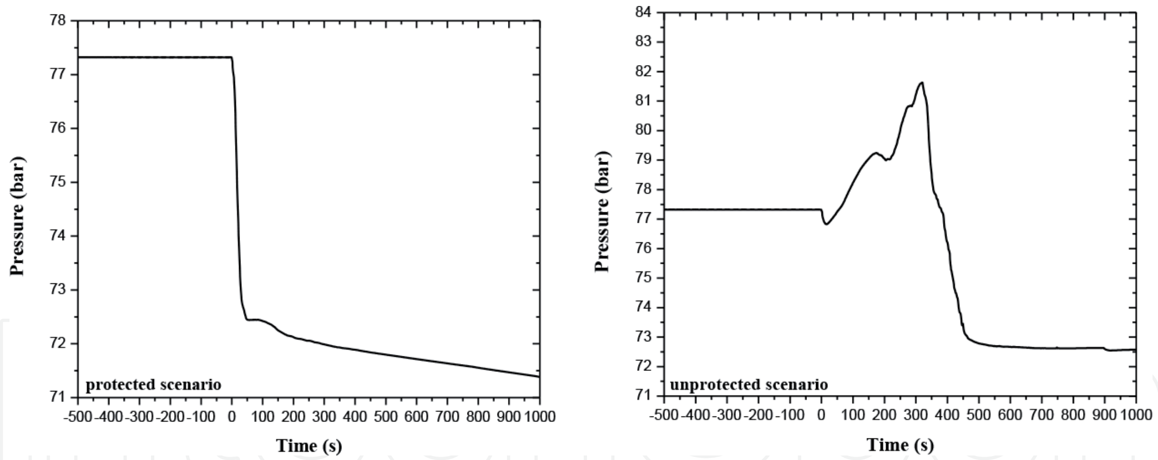


Figure 13.
Time variation of drum pressure.

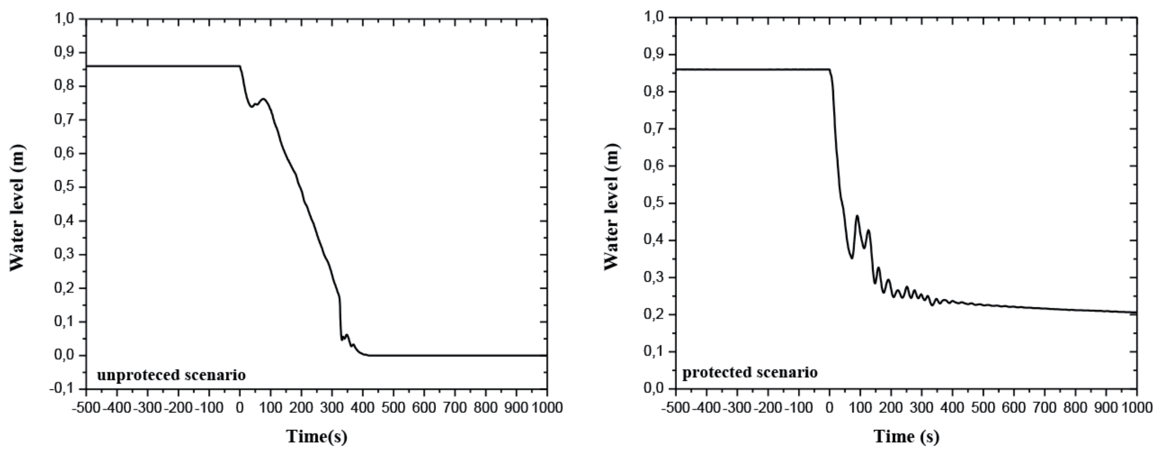


Figure 14.
Time variation of the drum water level.

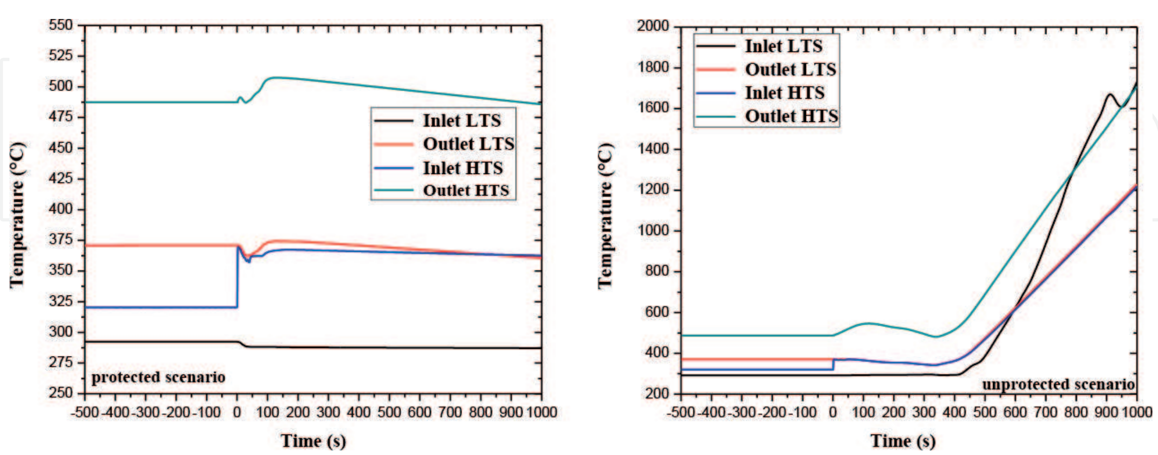


Figure 15.
Temporal variation of the superheated steam temperature inlet/outlet of the superheaters.

Figure 15 shows the time variation of the inlet and outlet temperatures of the superheated steam in low-temperature superheater (LTS) and high-temperature superheater (HTS). At steady state, the temperature values at the inlet and outlet of the two superheaters are, respectively, 292.6 and 370.8°C (LTS) and 321.2 and 487.3°C (HTS). After stopping the pump, temperatures decrease after stopping the burners. The protected scenario shows that the inlet temperature of SHT increases to the value of 370.4°C due to the lack of the desuperheating flow following the feed pump stop. Then it decreases to the value of 359°C. The temperatures increase again due to the heat inertia of the flue gases and then begin to decrease linearly. This decrease is caused by the cooling of the superheater by the ventilation airflow.

For the unprotected case, after stopping the pump, temperatures remain stable and then increase rapidly, reaching very high values of the order of 1720°C. This rise is due to the nonstop of the burners and the decrease of the steam flow rate.

In the steam boiler, wall tubes are designed to operate under highest heat transfer condition (1), where heat is supplied to the outer tubes' surfaces by the fumes. Therefore, and from the safety point of view, it is very important to know the evolution of the wall temperature of the vaporizer tube of the combustion chamber under accidental conditions. It is a key parameter in the safety analysis of the thermal installation. In natural circulation steam boilers, the vaporization regime is in every way in the form of nucleate boiling in order to ensure the continuous cooling of the wall heated by water [29]. As long as this vaporization regime is maintained, the inner wall temperature remains higher than that of the saturation.

The temporal evolution of the evaporator tube inner wall temperature and the heat transfer coefficient during transient for protected and unprotected scenarios is shown in **Figures 16** and **17**, respectively. Before the accident occurrence, the heat transfer inside the tubes is ensured by the nucleate boiling regime, which is characterized by a moderate internal wall temperature, of the order of 303°C, and a good

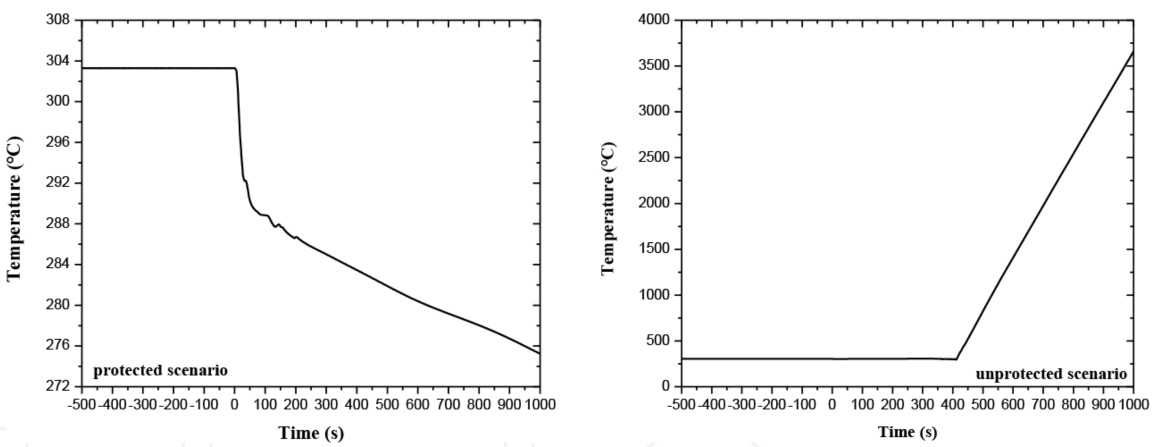


Figure 16.
Temporal variation of the inner wall temperature of the vaporizing tubes.

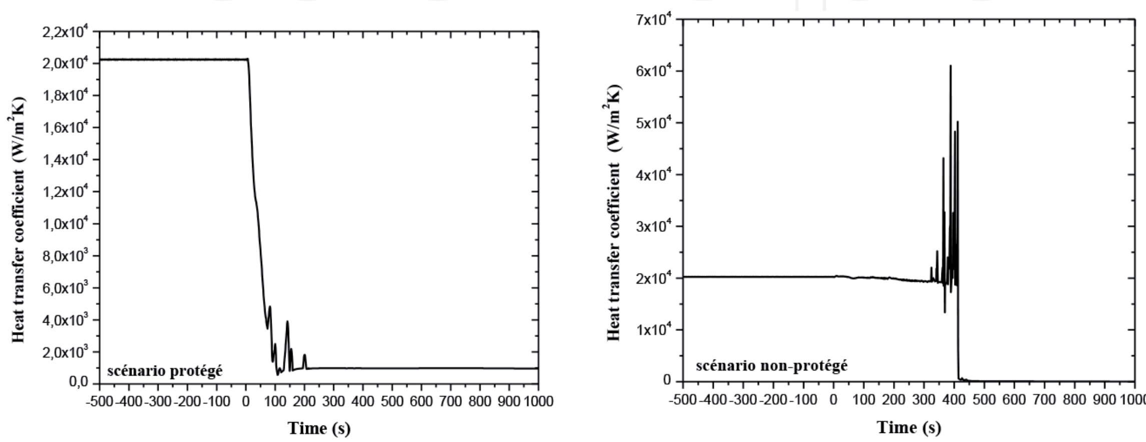


Figure 17.
Temporal variation of the heat transfer coefficient in vaporizing tubes.

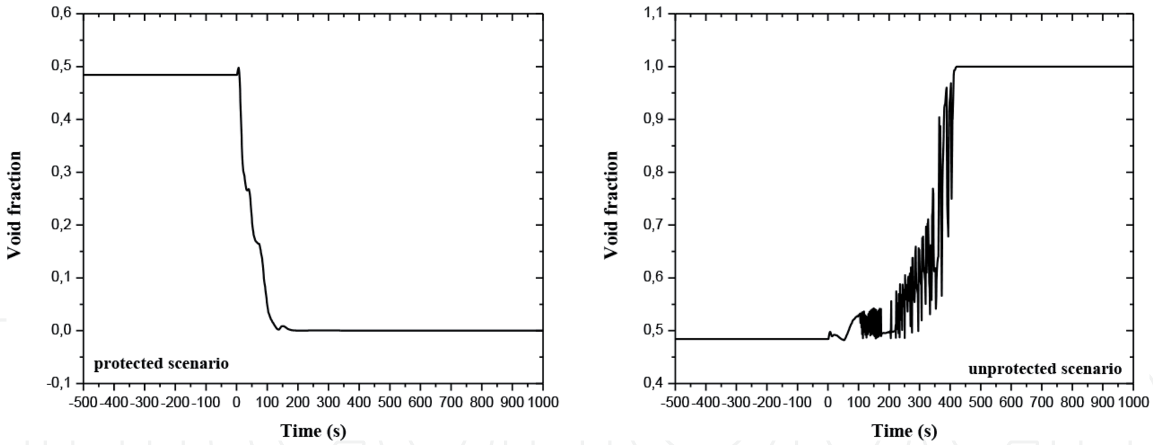


Figure 18.
Temporal variation of the void fraction in the vaporizer tubes.

heat transfer coefficient equal to 20.25 kW/m^2 K. Just after stopping the pump, the wall temperature drops from its initial value to 289.38°C, and the heat transfer coefficient drops from 20 to 5 kW/m^2 K in a time interval equal to 66 seconds. This drop is caused by stopping the burners; nucleate boiling is therefore stopped. Thereafter, the wall temperature decreases linearly until the end of the transient, and heat transfer is achieved by simple convection.

In the second scenario, instabilities in the heat transfer coefficient are observed, which implies that there is a poor heat transfer inside the vaporizing tubes, and the inner wall temperature is quasi-constant. From 410 seconds, the boiling crisis appears, leading to the dryout phenomenon. In fact, the liquid film becomes unstable and is depleted under the effect of intense vaporization. Hence, the wall surface dries out, the heat transfer coefficient drops sharply to 45.5 W/m^2 K, and the temperature of the inner wall increases rapidly to very high values (3900°C) due to the appearance of the boiling crisis. This temperature is higher than the allowed maximum operating value of the plant (500°C) [2, 22], which leads the melting of the vaporizer tube in the combustion chamber.

It is very important to study the void fraction variation during the transient to understand the flow behavior in both phases. **Figure 18** shows the temporal variation of the void fraction in the vaporizer tubes. For the protected scenario, we can see that before the accident (at steady state), the void fraction is maintained at the value 0.4837. After the accident, an instantaneous increase in the void fraction up to 0.4988 resulting from loss of feedwater is observed. After burner's shutdown, the void fraction becomes almost null, and the flow regime is characterized by liquid-phase convection.

During the unprotected case, the void fraction increases to reach unit, between the moment of the accident and the moment of the boiling crisis appearance; as it is shown, there are instabilities in the void fraction during its increase. These are probably caused by poor circulation inside the vaporizer tubes.

4. Conclusions

Modeling and thermal-hydraulic behavior simulation of an industrial water-tube steam boiler during the accidental transient using the RELAP5/Mod3.2 code are presented in this chapter. The transient investigated in this study is the loss of feedwater following the cost down of the feedwater pump. The transient was performed in two steps: the first one concerns the simulation of the protected scenario where the protection systems are operational, and the second one is the simulation of the unprotected scenario.

The results obtained make it possible to analyze and better understand the behavior and response of the installation to the accidental transients by the evolution of the steam boiler thermal-hydraulic parameters. Furthermore, the study clearly demonstrates the protective systems' role in preserving the structural integrity of the steam boiler.

This study has shown that the basic models of RELAP5 code give the possibility of reproducing the main thermal-hydraulic phenomena that may occur in the installation. Thus, it was possible to develop a basic model that can simulate steam boiler operation during normal and accidental transients. In addition, the capacity and reliability of the RELAP5/Mod3.2 code for thermal-hydraulic analysis of conventional thermal installations such as industrial steam boilers have been demonstrated.

Finally it was possible to demonstrate, using RELAP5 modeling capabilities, that in the case of safety and protection system failure, the critical phenomenon of the boiling crisis is established in the combustion chamber which is undoubtedly the cause of the frequent explosion of the steam boilers.

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