

Simulation of Loss-of-Flow Transient in a Radiant Steam Boiler with Relap5/Mod3.2

A.L.Deghal.Cheridi, A.Chaker, and A.Loubar

Abstract—loss of feedwater accident is one of the frequently sever accidents in steam boiler facilities. It threatens the system structural integrity and generates serious hazards and economic loses. The safety analysis of the thermal installations, based extensively on the numeric simulation. The simulation analysis using realistic computer codes like Relap5/Mod3.2 will help understand steam boiler thermal-hydraulic behavior during normal and abnormal conditions. In this study, we are interested on the evaluation of the radiant steam boiler assessment and response to loss-of-feedwater accident. Pressure, temperature and flow rate profiles are presented in various steam boiler system components. The obtained results demonstrate the importance and capability of the Relap5/Mod3.2 code in the thermal-hydraulic analysis of the steam boiler facilities.

Keywords—Radiant steam boiler, Relap5/Mod3.2 code system, Steady-state simulation, Transient simulation, Loss of feedwater accident

I. INTRODUCTION

STEAM boiler with natural circulation have a wide range of applications such as power cycles and industrial heating processes [1]. During operation, several problems may be encountered leading to limit the normal operation of the installations and generate serious disturbances in steam production program.

Loss of feedwater accident is considered as the most recurrent accident that occurs during steam boilers operation life time. This event is a result of pump power loss, pump failure, feed water line break or feedwater control valve closing [2]. In such case, water flow rate decreases suddenly, leading to a sharp decrease in steam boiler water level. Consequently, the natural circulation decreases affecting the heat transfer in steam generation tubes. A small circulation indicates a large void fraction in the tubes and possibility of poor heat transfer on the shell sides. Numerical simulation models have become an increasingly important design and analysis tool for boiler components and auxiliary equipment [3]. The simulation analysis using realistic system codes like Relap5/Mod3.2 will help understand the steam boiler thermal-hydraulic behavior during normal and abnormal conditions. This study is focuses on the analysis of a high power industrial steam boiler using

Relap5/Mod3.2 thermal-hydraulic computer code. It is an analysis system code of realistic evaluation level. It was developed at Idaho National Engineering Laboratory for the Us Nuclear Regulatory Commission (NRC). The code's generation has enabled its application to both nuclear and non-nuclear fields [4]. Relap5 computer code has well-known capabilities in handling two phase flow. The code uses a fast semi-implicit numerical method to solve the governing two-fluid non-homogeneous, non-equilibrium, six equation system.

In this work, the analytical investigation of the steam boiler thermal-hydraulic behavior during loss of feedwater accident caused by the pump power loss is discussed. The studied steam boiler is a radiant type, natural circulation, one drum and a combustion chamber in pressure. The steam boiler is installed in a typical complex of natural gas liquefaction. The boiler is designed to produce 374 tons/h of superheated steam at 73 bars and 487°C [5]. The transient analysis has been performed in two stages: a model validation against steady-state plant data, then the analysis results of loss of feedwater accident. The comparison shows a good concordance between the Relap5/Mod3.2 results and steam boiler operation data, proved the adequacy of the model, and demonstrated the capability of the code to reproduce the evolution of the main plant parameters.

II. STEAM BOILER DESCRIPTION

The steam boiler is installed in the complex of natural gas liquefaction; the unit generates a nominal steam capacity of 374 tons/h at superheated steam conditions of 73 bars and 487°C [5]. The steam boiler facility is subdivided into three main parts: the main feedwater line, the steam generator, and the main superheated steam line, fig.1 present a schematic representation of the installation. The steam generator evaporating tubes are heated by thermal radiation and convection [6]. In the combustion chamber, heat transfer is dominated by radiation, while conduction and convection contribute to less than 5% of heat transfer [7]. The thermal energy of the fuel gas exiting the furnace is transferred by convection to remainder of the boiler components (economizer tubes, superheater tubes). The rear pass receives two superheaters and tree economizers. The drum constitutes a necessary water reserve for the riser from what it receives the mixture of steam/water. Feedwater flows into the lower part of the drum according to the water quantity needed. Water in the drum flows into five downcomers and then flows through tubes in a riser (evaporating tubes) which are fabricated as membrane walls and vertical tube bundles. Water circulates due to the density difference of water in legs the loop.

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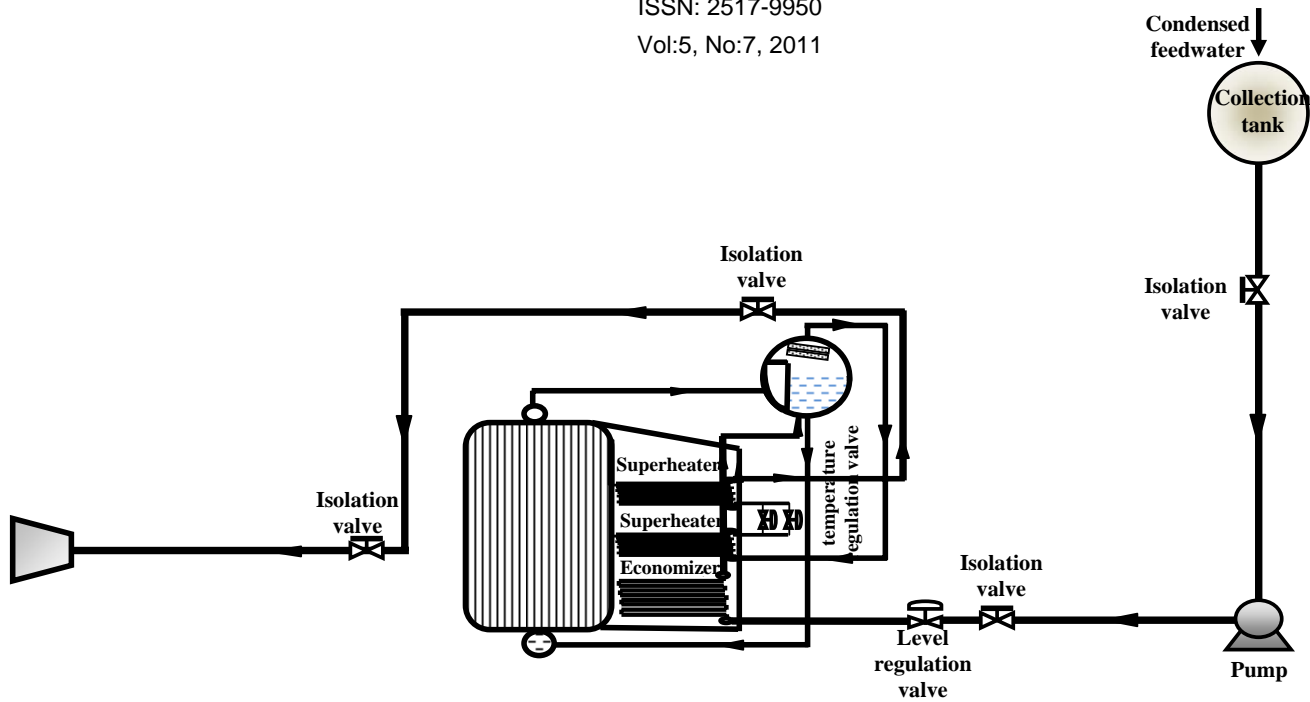


Fig. 1 Schematic representation of the steam boiler installation

III. NODALISATION AND SIMULATION

A. Relap5/Mod3.2 Presentation

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

model is one-dimensional, using a staggered mesh to calculate temperatures and heat flux vectors [9, 10].

B. Steam boiler modeling

The philosophy of using Relap5 code consists in subdividing the system in control volumes connected by flow junctions. The Relap5 steam boiler model consists of three main parts: the steam generator, main feedwater line and main steam line. The model includes 582 regular volumes, 571 junctions, 142 heat structures, and 7 time-dependent volumes. The nodalisation scheme is shown in fig.2.

The drum is modeled by BRANCH: 010, 015, 020, 025, the three safety valves, on the top of the drum are modeled by trip-valve components 007, 008, and 009 connected to time-dependent volumes 700, 800, and 900 respectively. The mixture water/steam collectors are modeled by the BRANCH, 030, 035, 040, 045, 050, 055, 060, and 065. The tubular screens and downcomer are modeled by the PIPE model component 115, 120, 125, 130, 135, 100, 110. The heat structure included in the model simulate the behavior of the material mass, and heat transfer between the material mass and the fluid in the system. The heat densities involved between the hot gases and the external tube surface are imposed by table entry [11]. It is entered as the right boundary conditions to simulate the convective heat exchanger related to convective section, as well as the radiation heat transfer in the furnace using the external heat exchange surface (S), the heat flux densities are obtained according to the relation $q=Q/S$ where Q is the transferred

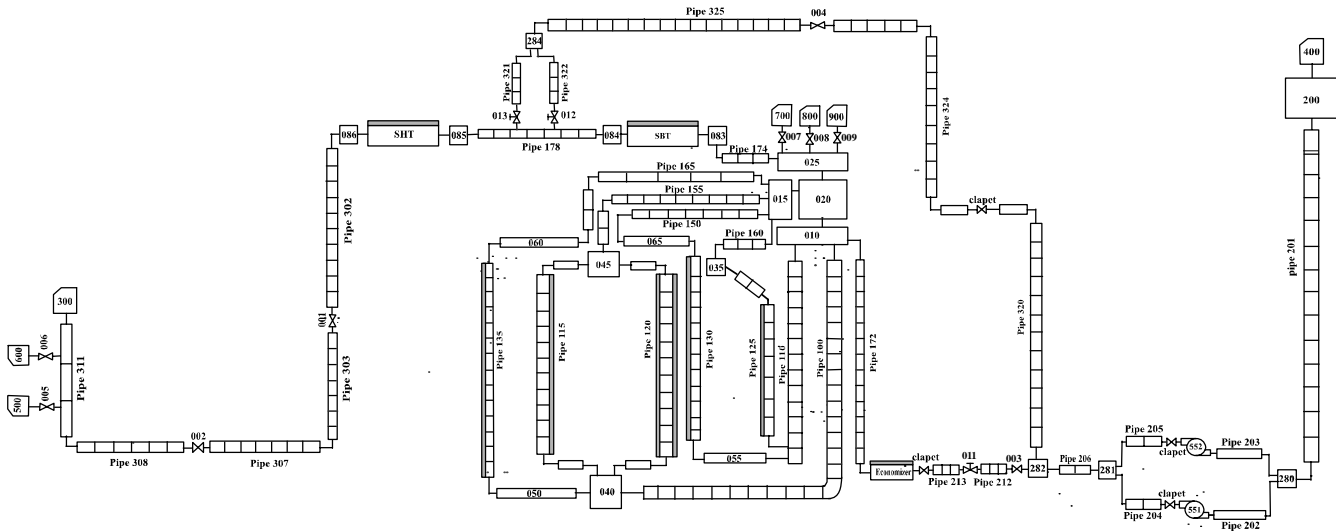


Fig.2 Relap5/Mod3.2 nodalisation diagram of the steam boiler

heat estimate from the energy balance between the hot gases and the boiler exchangers [12]. The main feedwater line is modeled using component BRANCH 200 to modeled the collection tank, the centrifuge feedwater pumps are modeled by the PUMP component 151 and 152, and the pipe line are modeled using the component PIPE 201 through 213. The feedwater is supplied by the condenser specified by time-dependent volume 400. To simulate the drum water level control valve, we used the component Servo-valve 011, and for the isolation valve we utilized the motor-valve 003. The economizer is modeled using 41 volumes, 40 junctions, and 20 heat structures (pipe 171). The main steam line includes: steam pipeline, the primary and secondary superheater, desuperheater temperature control system, isolation and safety valves. The pipeline is modeled by component PIPE 301 through 311, and the BRUNCH 083, 084, 085, 086. The superheater SBT and SHT are modeled using 16 volumes, 15 junctions, and 20 heat structures (pipe 176 and pipe 180) for each one. The isolation valves are modeled by motor-valve 001 and 002. The steam temperature regulation valve is modeled with two servo-valves 012 and 013. The desuperheater pipeline is modeled using the PIPE 320, 321, 322, 324 and 325. The safety valves are modeled using the trip-valve 006 and 005 connected to the time-dependent volume 600 and 500 respectively. Time-dependent volume 300 sets the boundary conditions of outlet superheated steam.

C. Accident description

Prior the accident, the steam boiler was operating under steady-state condition. The loss of feedwater transient is initiated when the pump costs down. The pump failure is immediately followed by a sudden decrease in feedwater flow rate. Consequently, an alarm signal is generated and the burners are shut down immediately. The imposed events involved in this transient are outlined in table. I.

TABLE I
IMPOSED SEQUENCE OF EVENTS

Time	Imposed events
-500-0 s	Steady-state regime
At 0.0 s	Feedwater pump cost down
After 0.25 s	Alarm signal is generated
At 5 s	Burners shutdown
At 1000 s	End of transient

IV. RESULTS AND DISCUSSION

A Relap5/Mod3.2 model is developed to analyze the loss of feedwater accident in the radiant steam boiler. The steady-state thermal-hydraulic parameter results are compared with the plant operating data. The transient obtained results are presented and discussed.

A. Steady-state calculation

In order to qualify the Relap5 model, the main thermal-hydraulic parameters of the steam boiler are compared to the available steam boiler operating data. The comparison between the steady-state predicted by Relap5/mod3.2 and the measured data of the steam boiler are presented in table. II. The calculated parameters are in good agreement with the steam boiler data.

TABLE II

COMPARISON BETWEEN PLANT AND CALCULATED DATA AT STEADY-STATE

Thermal hydraulic parameters	PLAN DATA	RELAP5 DATA
Exit steam flow rate (t/h)	374	374.357
Feedwater flow rate (t/h)	374	374.121
Outlet steam temperature (°C)	292	292.368
Drum pressure (bar)	76.9	77.2
Vapor pressure (bar)	73	73.199
Feed water inlet temperature (°C)	118	119.5
Outlet economizer temperature (°C)	287	287.03
Inlet SBT superheater temperature (°C)	292	292.316
Outlet SBT superheater temperature (°C)	370	370.848
Inlet SHT superheater temperature (°C)	322	320.141
Outlet SHT superheater temperature (°C)	487	487.338
Pressure at collection tank (bar)	1.89	1.89
Outlet pump pressure (bar)	91.93	94.15
Inlet steam generator pressure (bar)	82	78.2
Drum water level (mm)	860	860.003

B. Transient calculation

The transient calculation was carried out for 1000 s after the pump cost down. The transient main parameters curves describing the steam boiler behavior before and after the loss of feedwater accident are presented in fig.3 through 8. The parameters are: mass flow rate, drum level, drum pressure, void fraction, internal wall temperature and heat transfer coefficient. Fig.3 shows the feedwater and outlet steam flow rate variations. The feedwater and steam flow rates are initially equal to 374 t/h. As soon as the pump costs down, the feedwater decreases instantly. Due to the burners stopping, the steam flow rate decrease progressively during 90 seconds to vanish.

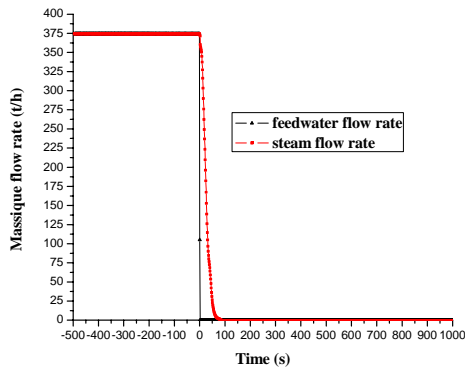


Fig. 3 Feedwater and steam flow rate

The water level in the drum indicates the amount of water stored in the drum-riser-downcomer loop. Is kept within a limited range for safety reasons. This water level is determined by two factors: total amount of steam/water in a drum-riser-downcomer loop and distribution of steam in the loop, these factors are affected by feedwater condition, steam demand, and heating rate in a riser [8]. The drum level response to the accident depends on a combination of water and vapor dynamics inside the steam boiler. Fig.4 shows drum water level behavior during the loss of feedwater transient.

Before the accident, the water level is maintained at its set point value of 860 mm in the drum. When the main feedwater pump cost down, the drum water level decrease rapidly to 359 mm and then continues decreasing until 206 mm, then the level remains at this value until the end of the transient. The decrease in the water level is a consequence of the system pressure drop (fig.5) in the drum due to the pump cost down.

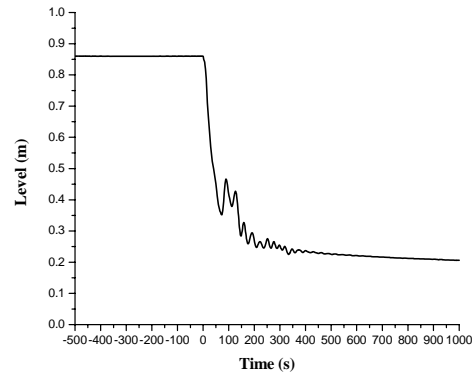


Fig. 4 Steam drum water level

The steam drum pressure variation during accident is given in fig.5. After the occurrence of accident and the stop of the burners, the pressure decreases progressively to 72.44 bars during 58 second. Then, there is a decrease of pressure until the end of the transient which is induced by the cooling of the steam boiler by the external air cooling.

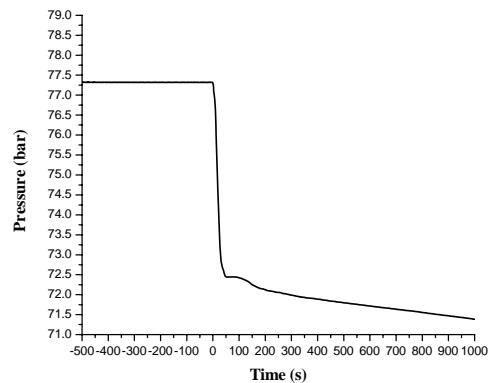


Fig. 5 Steam drum pressure

The time history plots of both internal wall temperature and the heat transfer coefficient are respectively shown in fig.6 and 7. Initially, the internal wall temperature is 303 °C and the heat transfer coefficient is 20.25 KW/m²K. After the occurrence of accident, the temperature decrease from its initial value to 289.38 °C also the heat transfer coefficient from 20 to 5 KW/m²K during 66 seconds as a result of burner's shutdown. After, the wall temperature decreases linearly until the end of the transient due to the outside air cooling and the convective heat transfer in the tubes inner wall

(liquid phase).

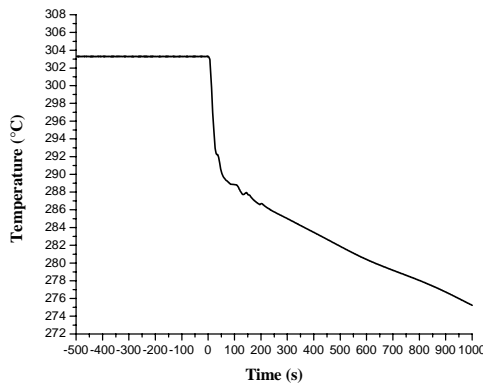


Fig. 6 Internal wall temperature

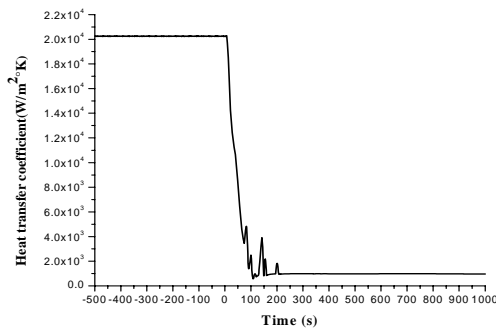


Fig. 7 Heat transfer coefficient

It is important to investigate the void fraction variation during the transient to well understand the two phase flow behavior in the steam boiler. Fig.8 shows the history plot of the void fraction in the evaporator tubes. At steady-state, the void fraction is 0.4837. After the costs down of the feedwater pump and the burner's shutdown, the void fraction decreases rapidly.

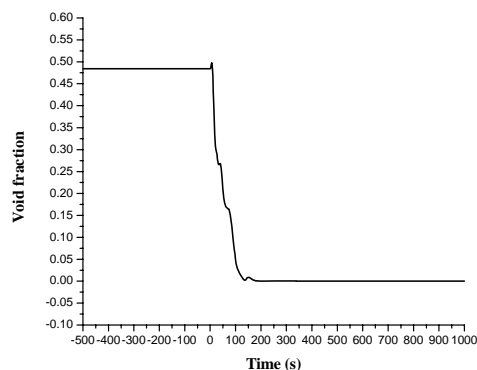


Fig. 8 Void fraction

V. CONCLUSION

The aim of this study is to investigate the thermal-hydraulic behavior of the industrial radiant steam boiler under steady-state and loss of feedwater accident caused by a cost down of the pump using the thermal-hydraulic code Relap5/Mod3.2. A complete plant model has been made, improved, and validated against available plant data.

A good agreement between the numerical results and the steam boiler operating data for the steady-state is obtained. During the transient, the thermal-hydraulic parameters: flow rates, drum water level and pressure, internal wall temperature, heat transfer coefficient and void fraction variation are used to assess the system response to the accident and how control systems can successfully mitigate the consequences.

The steam boiler Relap5 model has proved satisfactory; and the model was capable of predicting all of thermal-hydraulic transient features of the radiant steam boiler. The obtained results demonstrate the Relap5 code capability to predict the main phenomenon taking place in whole system of the steam boiler.

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