Annals of Nuclear Energy 97 (2016) 27–35

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Numerical simulation of a 374 tons/h water-tube steam boiler following a feedwater line break

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ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form 28 March 2016
Accepted 18 June 2016
Available online 28 June 2016

Keywords:
Industrial water-tube steam boiler
RELAP5
Modeling
Safety
Accident analysis
Feedwater tube rupture transient

ABSTRACT

To ensure the operational safety of an industrial water-tube steam boiler it is very important to assess various accident scenarios in real plant working conditions. One of the most challenging scenarios is the loss of feedwater to the steam boiler. In this paper, a simulation of the behavior of an industrial water-tube radiant steam boiler during feedwater line break accident is discussed. The simulation is carried out using the RELAP5 system code. The steam boiler is installed in an Algerian natural gas liquefaction complex. The simulation shows the capabilities of RELAP5 system code in predicting the behavior of the steam boiler at both steady state and transient working conditions. From another side, the behavior of the steam boiler following the accident shows how the control system can successfully mitigate the effects and consequences of such accident and how the evaporator tubes can undergo a severe damage due to an uncontrolled increase of the wall temperature in case of failure of this system.

1. Introduction

Water vapor is an energetic fluid very used in industrial processes. It is found in several activities such as petro chemistry, processing industries, district heating, electrical facilities, and others (Moghari et al., 2012). Steam generators are vital to power and processing plants; they can be classified according to various parameters (Adam and Marchetti, 1999). But, in general they are classified into two categories: fire-tube and water-tube steam boiler. In recent years, water-tube steam boilers have received great attention due to their benefits in terms of costs, simplicity, and more particularly inherent safety (Walter and Linzer, 2006). Since the steam boilers operate at high temperature and high pressure conditions it is of great importance to make an effective assessment of their safety under abnormal situations. However, such facilities are subject to several operating failures and accidents, which could expose the system to technical problems and serious hazard (Rahmani et al., 2009). The accidents occur due to various reasons: pipeline break, equipments failures and so on. It is consequently necessary to perform accident analysis and evaluate causes and consequences of possible accidents (Diaz, 2001). Therefore, special attention is considered towards their safety.

Assessment of power plants safety is largely based on numerical simulation (Smrekar et al., 2009). Since these facilities are very complex systems, it is very difficult to carry out tests directly from both technical and economical points of view (Sun et al., 2002). In comparison with experimental and analytical methods, numerical simulations are also efficient tools for safety and integrity assessment (Damir, 2000).

Currently, with the calculation codes such as: APROS, RELAP, CATHARE, and ATHLET it has become possible to provide the thermal hydraulic behavior of the facilities and to reproduce the physical phenomena occurring during normal and accidental operation (Nematollahi and Zare, 2008; Reis et al., 2010). These computer codes are the result of scientific research conducted for several decades by international collaboration in the field of safety and design of nuclear power plants. However, they can also be used to study the normal and accidental operation of industrial installations (Rahmani et al., 2009; Deghal Cheridi et al., 2013; Ferri et al., 2008; Kaliatka and Valincius, 2012).

The purpose of this work is to develop a RELAP5 model for an industrial water-tube steam boiler. Once the model qualified at the steady state level, it is used to analyze the behavior of the steam boiler following a loss of water accident caused by a rupture on the feedwater line connecting the economizer to the steam drum. It is one of the frequently sever accidents encountered in steam boiler installations. To carry out this study, a nodalization of the steam boiler has been developed based on RELAP5 requirements. The validation procedure of the developed model was performed using the experimental available data of steam boiler.

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http://dx.doi.org/10.1016/j.anucene.2016.06.021
0306-4549/

2. Steam boiler operation and modeling

2.1. Boiler description

The studied steam boiler is a radiant water-tube natural circulation type. It is installed at the SONATRACH natural gas liquefaction complex (GL) of Skikda to generate a steam capacity of 374 tons/h (Deghal Cheridi et al., 2013; Manuel Tech., 2000; Deghal Cheridi and Chaker (2008, 2011)). The role of this boiler is to ensure the supply of the unit with superheated steam primarily for driving a turbine.

The main components of the steam boiler are:

- One drum
- Three economizers
- Tow superheaters (low and high temperature)
- Desuperheater
- Integrated control and monitoring system
- Tow centrifugal pumps
- Isolation, safety and flappers valves
- 12 burners at three levels
- Feedwater and steam piping
- Furnace and rear pass
- Collection tank
- Downcomers and riser tubes

The main operating parameters of the steam boiler are presented in Table 1 and a schematic representation is illustrated in Fig. 1. A more detailed description of the steam boiler is given in Ref. Deghal Cheridi et al. (2013).

Fig. 2 illustrates water, steam and combustion gases circulation in the steam boiler. The combustion gases leave the furnace by a common wall separating the two tube sections. The direction of flue gases flow is vertical down in the rear pass passing through the high temperature superheater (HTS), low temperature superheater (LTS), and economizers. These gases are then sent to the atmosphere through the chimney.

The steam boiler is fed with unpolluted condensed water from the collection tank using the pump. This feedwater before entering the drum is heated in the economizers which are located in the flow of combustion gases exiting the furnace. The feedwater flows downward through downcomers. Thereafter, feedwater flows towards the evaporators' tubes in the combustion chamber and in the rear pass where it is heated in the water walls and partially transformed into steam.

The water/steam mixture rises to upper collectors to get into the drum. This circulation loop is made by the natural circulation produced by the difference in densities between the feedwater in the downcomers tubes and the water/steam mixture in the riser tubes (Deghal Cheridi et al., 2013).

Inside the drum, the steam separates from the water naturally. The water is collected in the liquid compartment and the steam exits to the steam dome. The saturated steam is piped out of the drum to the superheaters (HTS and LTS) where its temperature rises to 487 °C.

Table 1
Main steam boiler operating parameters.

Technical parameters	Units	Values
Feedwater temperature	°C	118
Efficiency	%	92
Air excess	%	1.3
Air flow rate	Nm^3/h	344,800
Natural gas flow rate	Nm^3/h	45,699

2.2. Nodalization and simulation

In order to perform accident analysis of the steam boiler, RELAP5/Mod3.2 system code is used. It is a best-estimate thermal-hydraulic code developed at Idaho National Engineering and Environment Laboratory (INEEL) for the US Nuclear Regulatory Commission (USNRC). It has been developed for transient simulations of a light water reactor (LWR) coolant system during postulated accidents (RELAP5 Manuals, 1998). RELAP5 is a highly generic code that can be used for simulation of a wide variety of transients in nonnuclear systems (Deghal Cheridi et al., 2013; Ferri et al., 2008; Kaliatka and Valincius, 2012; Rahmani et al., 2009). The hydrodynamic model of RELAP5 is based on non-equilibrium, non-homogeneous, and six equations system for the two phases that is solved by a fast, partially implicit, numerical scheme. RELAP5 have many generic components models, In addition, special process models are included for effects such as flow at an abrupt area change, form loss, branching and choked flow (RELAP5 Manuals, 1998).

The RELAP5 model of the steam boiler facility was developed for analysis of normal and abnormal operational occurrences. The data required for the modeling process were obtained from the steam boiler documentation and staff (Manuel Tech., 2000). The development of the RELAP5 model is based on the technical and geometrical information of the steam boiler (elevation, diameters, sections, roughness, length, and heat information). Basic information on the nodalization is presented in Table 2.

The nodalization diagram is presented in Fig. 3. The collection tank is modeled using branch component 200. Pump components 551 and 552 are used for the two centrifugal feedwater pumps. Pipe components 201 through 213 are used for modeling the feedwater pipe lines, 301 through 311 for steam pipe lines, 320 through 325 for desuperheater pipe lines, and 100 and 110 for the downcomers. The tubular screens of the furnace and rear pass are modeled by the pipe components 115, 120, 125, 130 and 135. The servo-valve component 011 was used to control the drum water level, and two servo-valve components 012 and 013 were used to control the superheated temperature control valves. For the isolation valves, we used the trip-valve components 001, 002, 003, and 004. The flapper valves are modeled by the Check-valve component. The economizer is modeled by the pipe component 171 using 41 control volumes, 40 junctions and 20 heat structures. The superheaters LTS and HTS are modeled by pipe components 178 and 180 respectively using 16 control volumes, 15 junctions, and 20 heat structures for each one.

The steam drum is modeled using four brunch components 010, 015, 020 and 025 and related junctions. The 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 to impose the atmospheric conditions. All the collectors in the installation are modeled by the Branch components (280 through 284 for feedwater pipe line, 034 though 045 for the steam generator and 083 through 086 for the steam pipe line).

The boundary conditions representing the condensed feedwater entering into the collection tank and the superheated steam going to the turbine are modeled respectively by time-dependent-volume components 400 and 300. More details on the steam boiler nodalization can be found in Ref. Deghal Cheridi et al. (2013).

The heat structures used in the model simulate the thermal behavior of the steam boiler, namely energy storage and heat transfer between the wall tubes and the fluid in the facility. The heat exchangers are presented by heat structures connected to pipes 171, 176 and 180, the furnace is presented by heat structure connected with pipes 115, 120 and 135; and rear pass section is presented by heat structures connected with 125 and 130. The technical parameters presented in Table 3 enable the estimation