Using Numerical Simulation to Diagnose Boiler Tube Failures

Eric Duplain, Eng, M.Eng.[1*], Luc Gravel[1], Eng. Ph.D., Peter Tye[1], Ph.D.

[1]Brais, Malouin & Associates, 144 Barr st., St-Laurent, Quebec, Canada

[*]eduplain@bma.ca

1. Introduction

A VU-60 type boiler has been commissioned in 1999 for a water desalinization plant. It is used for the production of 369 tonne/hr of saturated steam at pressure of 22 barg. Natural gas is fired through six front fired burners which can be adjusted in the field to obtain an appropriate flame shape for a given furnace.

Since 2001, this boiled experienced many tube failures event at full load capacity. In December 2017, multiple tube failures were reported at the entrance of the convection bank (fig. 1). These tube failures occurred shortly after the trip of a heat recovery steam generator (HRSG), which caused a sudden steam pressure drop from 16 to 9 barg.

Following this event, an investigation was launched to determine the cause. For this, numerical tools are used to detect potential causes, both on the fire side (furnace/convection bank) and in the water/steam side (inside the riser and downcomer tubes).

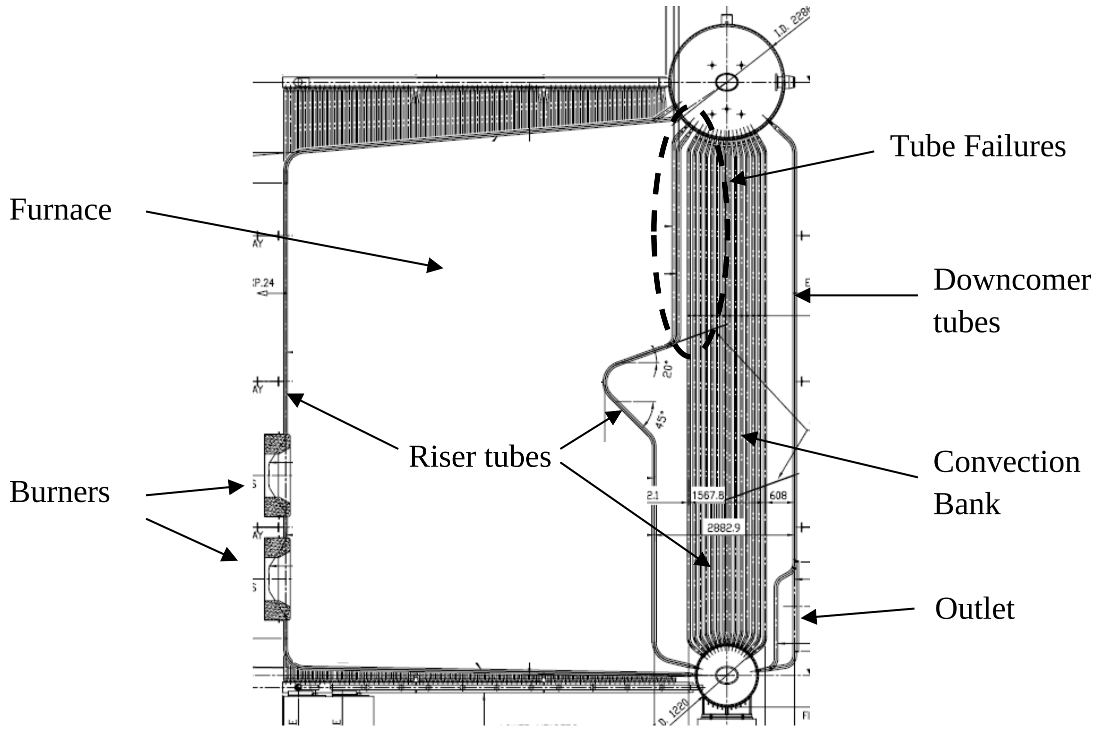


Figure 1. Schematic representation of a VU-60 Boiler

2. Material and Methods

First, Computational Fluid Dynamics (CFD) was used to simulate the combustion of natural gas in the furnace. The goals of this simulation are to obtain the flow & temperature fields throughout the furnace and the convection bank, to obtain the heat fluxes on the furnace tubed walls for the subsequent water-steam circulation analysis, and ultimately to detect any potential problems related to the combustion in the furnace. For this, the commercial code Star-CCM+ from SIEMENS was used. The physical models implemented are the following:

- Time: Steady state
- Space: Three-Dimensional
- Flow: segregated Flow and Fluid Enthalpy
- Combustion: Steady Laminal Flamelet with Chemical Equilibrium (since the burners produce diffusion flames, not premixed)
- Radiation: Gray Thermal Discrete Ordinate Method with participating media
- Turbulence: RANS 2-Layer Realizable All y+ k-epsilon
- The convection bank is modelled as a porous medium
- Refractory covered portions are considered as thermal resistances

Moreover, the air velocity profile at the burners faces was obtained through a detailed simulation of one burner. The gas, which is injected at 1.5 barg, is introduced into the computational domain at furnace pressure to avoid compressibility effects, but at sonic velocity for the conservation of injection momentum. Also, because the gas injectors orientation in the burners was unknown, two limiting cases were simulated.

The computational domain was discretized into a mesh comprised of 14 million polyhedral cells with refinements in front of the burners, where high velocity, temperature and species concentration gradients are expected. The use of this code, the physical models implemented and the mesh size) has been validated over the years with numerous boiler simulations for which operation and performance data were made available.

Second, a water circulation analysis was performed using the wall heat fluxes obtained from the previous CFD runs. This analysis is carried out using an in-house developed tool that calculates the detailed two-phase mixture in each tube subject to heat fluxes and constrained by a common drum-to-header pressure differential. More specifically, it solves the basic equations governing the physics of two-phase steam water flows and boiling heat transfer applied to boilers with natural circulation. It uses a four equations drift flux model (1D, simple & fast yet accurate) to describe the behavior of the two-phase steam-water mixture. The equations solved are the equations of conservation of mixture mass, momentum and energy as well as a constitutive equation, which accounts for the unequal velocities between the vapor and liquid phases. The phenomena of subcooled boiling and subcooled vapor generation are also taken into account. This code has been validated with over 10k measurement points at Ecole Polytechnique de Montreal.

The outputs of this simulation include, for each tube of the boiler, the quality, the void fraction, the phases velocities, the phases flow rates, the tube metal temperature, and the flow regimes (fig. 2). As such, phenomenon such as intermittent dry out and steam blanketing, which are often the cause of internal deposits and ultimately overheating and failure, can be detected. The flow rates can then be summed over the entire boiler to obtain the total circulation, which is also indicative of the boiler performance.

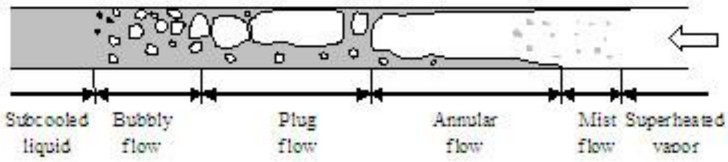
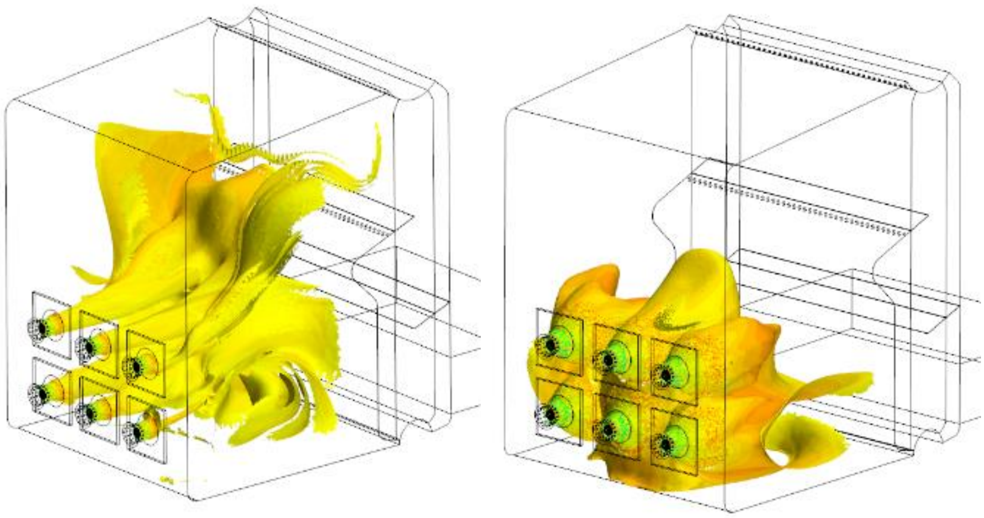


Figure 2. Example of flow regimes in a horizontal tube (Collier 1995)

3. Results and Discussion

Figure 3 presents the iso-surfaces of luminous flame contours for both gas injector limiting cases. For one of the two cases (a), the flame reaches the entrance of the convection bank in the area where the tubes failures were reported. Also, this creased a preferential path for the hot gases in the same region of the convection bank. This indicates that depending on the actual gas injectors orientation in the burners, long term overheating may have weakened the tubes at the location of the reported tube failures.



(a) (b)

Figure 3: Isosurfaces of luminous flame contours for gas injectors oriented (a) toward the center, and (b) axially

The heat fluxes corresponding to the case which led to fig. 3 (a) were then fed to the circulation code. It was found that the tubes on the side walls close to the region where the tube failures occurred have low circulation due to their bottom portion receiving low heat flux in the convection bank. When the heat flux gets stronger at the top, they see a rapid increase in quality and void fraction, thus the possibility of steam blanketing given that they are vertical tubes.

Another striking finding for this boiler was the circulation ratio (total flow divided by total steam flow), which was about 8 for both cases. For the operating pressure of this boiler, literature have shown that this ratio should be in the order of 20 to 30. This lack of circulation can be visualized in fig. 4: as the load of the boiler increases, the rate of increase in total circulation decreases, and the total circulation almost reaches a plateau.

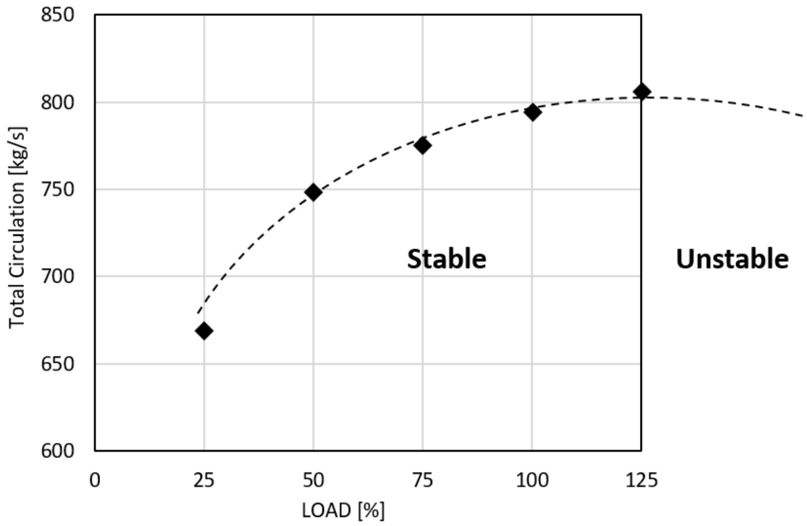


Figure 4. Total circulation of the boiler as a function of load

Operating a boiler in the unstable region of the flow vs. load curve of a boiler is dangerous as it can lead to a runaway decrease in flow, which could cause overheating and eventual boiler tube failure: additional heat input decreases the circulation, thus the cooling of the tubes.

4. Conclusions

This methodology of using CFD along with an in-house tool allowed us to determine a likely course of events that led to the tubes failures.

First, the burner gas injectors adjustment might have caused long term fatigue in the region around the failed tubes. This long-term fatigue was also exacerbated by the fact that the total circulation of the boiler is insufficient by design: not enough flow in the tubes can lead to a situation where the flow regimes are such that steam blanketing can thermally insulate the tube, thus increasing its surface temperature beyond normal operating values.

Then the pressure drop event caused the void fraction in the downcomers to increase from 0% to 93% instantaneously, which caused the circulation in the boiler to stop entirely, thus the cooling of the tubes. The time allowed before the boiler was shut down was enough to cause a short-term overheating and the subsequent failure previously weakened by long-term overheating. Having insufficient total circulation also puts the boiler dangerously close to an operation that can lead to a runaway decrease in flow, which could also cause overheating and eventual boiler tube failure, even in the absence of short or long-term overheating.

Naturally, the gas injector orientation must be adjusted carefully to avoid flame quenching and preferential paths for the flue gases in the convection bank. Also, the total circulation of the boiler should be increased by adding large, unheated external downcomers.