Simplified approach for creep evaluation in superheaters

IOP Conf. Series: Materials Science and Engineering **776** (2020) 012044 doi:10.1088/1757-899X/776/1/012044

Simplified approach for creep evaluation in superheaters

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Abstract. This paper is focused on the estimation of temperature distribution on superheater tube bundles for the consequent creep damage evaluation. The precision of estimated temperatures is very important because it significantly affects residual creep life. Conditions in the tube bundle can be simulated using CFD, however, a full 3D simulation would be computationally intensive and not fit for practical use. In order to mitigate this issue, the new approach considered in this paper uses a series of 2D CFD simulations in multiple sections using known inlet flow conditions. Those conditions have been investigated in previous work using 3D CFD simulation of flue gas flow starting in the combustion chamber and ending just before the superheater in the second pass. The paper also deals with possible temperature differences that may arise due to simplifications in the proposed approach. Lastly, the residual creep life is estimated using obtained temperature distribution on the tube bundle.

1. Introduction

A boiler is a device which is producing steam (or sometimes also hot water) using heat received by burning the fuel. There are three basic types of fuel commonly burnt: gas (e.g. natural gas), liquid (e.g. oils) and solid (e.g. coal). These days burning of alternative fuels is also very popular but it often leads to various problems and necessity for design optimization. Therefore, fuel type being burnt strongly affects the choice of the main boiler components. The required amount of steam (produced for consequent use in a turbine or other processes) determines the boiler size. Burning different types of fuels also affects flue gas composition. Burning the gas fuel produces almost no ash in comparison with other types of fuels, that can often cause significant problems [1–3].

High efficiency, reliability and optimal fuel flexibility are the most valued boiler attributes these days. Those new demands are reflected in the demand for boilers with higher standards, higher efficiency, the possibility of burning different fuels and larger sizes, but with a lower environmental impact. There are various types of boilers, they can be divided into several categories based on e.g. medium inside the boiler tubes, state of produced medium, the purpose of use, operating pressure, circulation of the liquid, design of the combustion chamber [1, 4].

1.1. Basic boiler components

Even though there are various types of boilers, they have several common crucial parts. Those can be divided into 3 basic categories [5]:

- Combustion equipment with accessories – it mainly consists of furnace with burners or grate. In this part burning process is realised. These crucial parts are followed by additional equipment such as equipment for fuel preparation, device for capturing of solid residues from flue gasses (in case they

are present), preheaters of combustion air, air fans, ash separators and equipment for removing pollutants from the combustion process.
- Exchanger part – in this part, water is being warmed up, after that the water is being evaporated and later superheated to produce superheated steam of required parameters.
- Devices for measurement and regulation – those devices are inseparable part of each boiler. Their main purpose is to ensure a smooth, reliable and safe operation of the boiler. This group includes various thermocouples, valves, blowers, chimney and more.

This article focuses on exchanger part, mainly superheaters, which are often one of the most exposed parts of the boiler. They are exposed to high temperatures, aggressive environment, and other types of load often for decades.

1.2. Boiler damage types
Boiler service life is often decades thus some kind of damage is basically unavoidable. Even though damage of the boiler often occurs as a combination of different types of damage, each type is unique with different impact, severity and influence on service life. Based on damage root cause the basic damage types can be divided into five categories [3, 6–8]:
- temperature (creep, long-term and short-term overheating),
- corrosion (waterside, fireside),
- flow-related (erosion, cavitation, fouling, slagging),
- operation (e.g. change of fuel, incorrect regulation, sudden load change),
- construction (e.g. improper equipment design, material misuse).

Boiler superheater, which is the main focus of this article, is basically the tube bundle with internal pressure. Those tubes are alongside steam generators the crucial part of water tube boilers. It is caused by exposure to high temperatures and pressures on the steam side as well as flue gas side.

1.3. Temperature-related damage
This article focuses on temperature-related damage which is a common problem of tube bundles located in boilers. High temperature may lead to material overheating as well as creep which in combination with flue gasses may cause high-temperature corrosion. Material properties are extremely sensitive to temperature, therefore these conditions in combination with imperfect design methods may lead to high-temperature damage. To determine damage caused by overheating, detail analysis and investigation of damaged components is necessary. Increase of temperature may be caused by oxide scales growth (from inside or outside) or because of insufficient "coolant" flow rate in the tubes. High temperature, as well as stresses, aggressive environment, corrosion degradation and other, can significantly reduce service life of the boiler components, however proper material selection can increase their resistance [9].
There are two basic types of temperature related damage:
- Short-term overheating – It is caused by material temperature exceeding design values for a short time, yield strength is reduced and it may be exceeded by stresses causing plastic deformation, thinning the walls and in some cases, it may lead to wall rupture due to exceeding of tensile strength. The main cause of short term overheating is the lack of coolant flow [6].
- Long-term overheating – It is the most common cause of damage in boilers mainly affecting tube bundles. It is a result of a combination of temperature, time, stress and material properties. Long-term overheating, may result in tube rupture.

According to standards, the influence of temperature is reflected in maximal allowable stress value, therefore to prevent temperature-related damage, the proper material selection (during the design of boilers and pressure vessels) is crucial. Carbon steel is the most common material being used for boiler construction because of its price. However, its material properties are often not sufficient for higher temperatures, therefor exposed tubes are often made of low alloyed steel (with molybdenum for better creep resistance and chrome also for better creep resistance as well as slowing down of high-temperature corrosion) [1, 6].

2. Investigated boiler description

Three-staged boiler with natural circulation and steam production 60 t h^{-1} is being analysed. The boiler was designed for burning natural gas heavy fuel oil and tar mixtures, however, several other fuel types were burnt in this boiler during the service life.

Boiler main parts are shown on the scheme (Figure 1). The burning process starts in four low emission burners combined with flue gas regulation system. They were used to reduce NOx emissions in order to meet legislation limits. Membrane walls of the first stage (combustion chamber) and second stage work as evaporators. In the second stage two superheaters are located as well as an economiser. In the third stage, the second economizer is located.

This article focuses on superheater P2, which is located as the first tube bundle in the second stage of the boiler. It is basically a horizontal tube bundle located in counterflow and which consists of 3 rows each with 66 tubes. All those 198 tubes then create 6 passes for the steam.

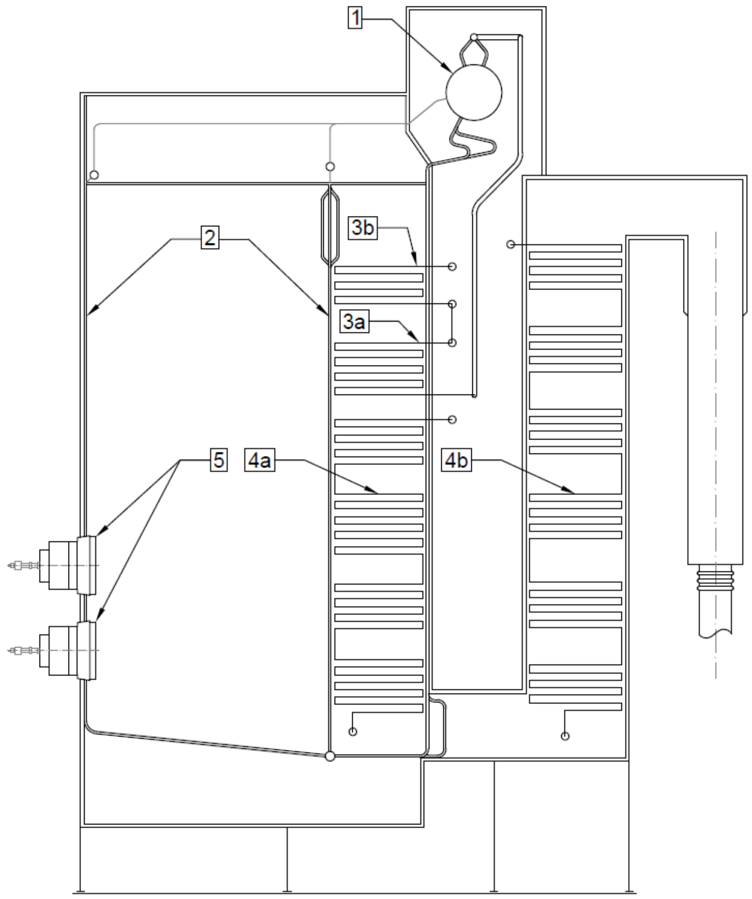

Figure 1. Simplified boiler scheme (1 – boiler drum, 2 – evaporator/membrane walls, 3a – superheater P1, 3b – superheater P2, 4a – economizer E1, 4b – economizer E2, 5 – low emission burners) [3].

2.1. Boiler parameters

During boiler analysis, there are several crucial parameters which are considered. One of the most important is boiler service time 62000 h (at the time of experimental data collection). Other boiler parameters can be divided into two basic categories (all parameters are for natural gas combustion) [3]:

- Design parameters:
  - Steam production: 60 t h^{-1},
  - Superheated steam temperature: 365 °C (+23 °C, -10 °C),

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- Superheated steam pressure: 3.82 MPa,
- Feed water temperature: 145 °C,

- Real parameters during natural gas combustion:
  - Steam production: 35–95 t h^{-1},
  - Superheated steam temperature: 340–385 °C,
  - Superheated steam pressure: 3.45–3.65 MPa.

The design parameters differ from the actual operation parameters, so it wasn't acceptable to use them. Since operation parameters were not sufficient and a lot of data was not measured or was missing, it was necessary to perform several calculations in order to obtain them. Missing parameters were calculated and described in previous work [3] and are now used.

3. Simplification from 3D to 2D

The superheater thermal load was calculated in previous work [3]. Obtained results are being used as boundary conditions in subsequent analyses. By complex 3D simulation, thermal load on the superheater tube bundle was calculated. However, to estimate the remaining creep life, it is necessary to calculate superheater tube surface temperatures.

To evaluate this temperature, it is necessary to simulate flue gas flow around tubes. For temperature related damage evaluation simplification to 2D geometry was used. These simulations are sufficient for our purposes so there is no need for complex 3D simulation. Five cuts across the domain of superheater in X direction were used as shown in fFigure 2 (cuts X1 to X5). The size of the domain is 3000 × 1301.8 × 5025 mm (W × H × D), while the first cut is made 300 mm from membrane wall and all the others are 600 mm far from the previous one.

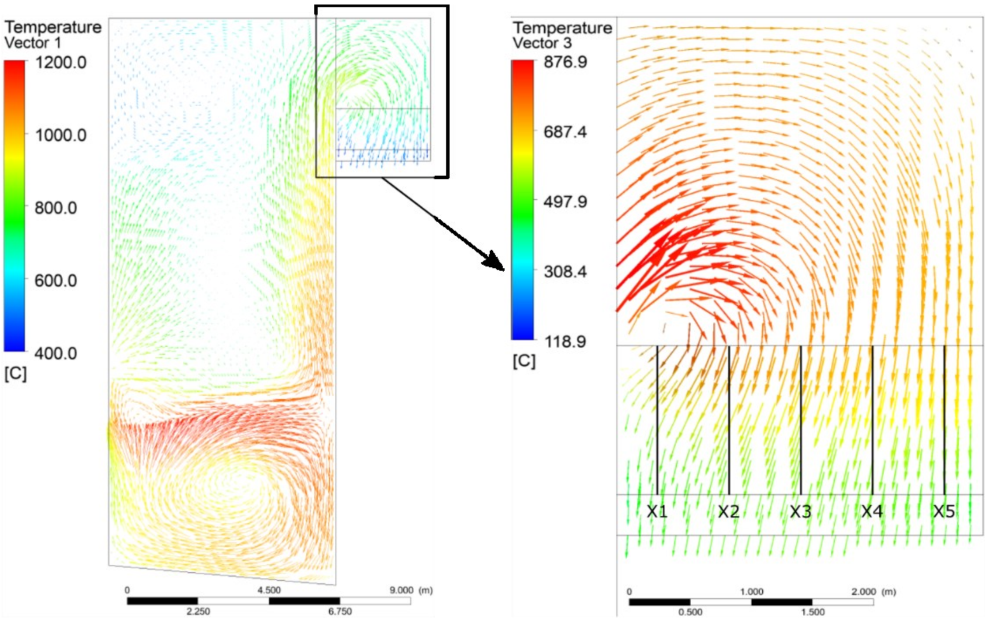

Figure 2. Results from 3D simulation from previous work with locations of domain cuts for 2D simulations.

3.1. Computational 2D model

2D model was created to simulate fluid flow around the tubes (Figure 3). The model is divided into three parts. The first and third part is an area with tubes and it simulates first and the last pass of the superheater, the second part is simplified to porous zone (instead of four passes) to save calculation time. The porous zone was used to simulate local resistance of tubes as well as simplified heat transfer.

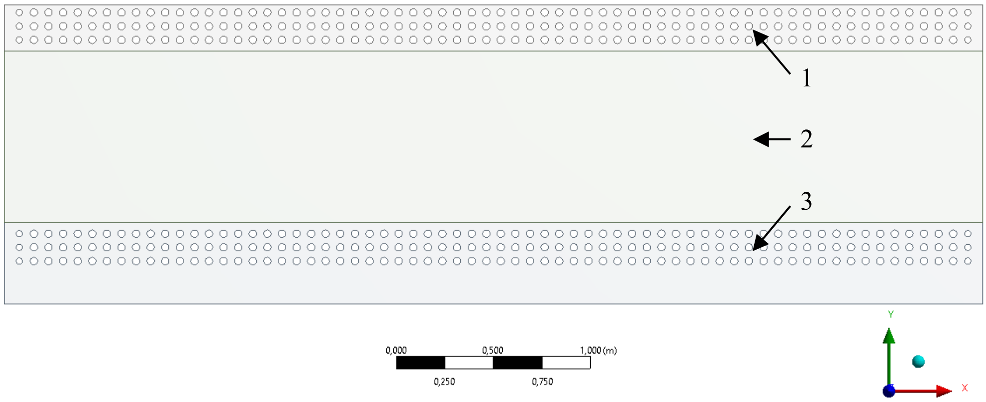

Figure 3. Geometry of simulated 2D domain.

3.2. Boundary conditions

The porous zone was defined by coefficient of local resistance C2 = 12.544 m^{-1} and medium porosity ϕ = 0.7887. As mentioned the porous zone also takes away the heat set up as specific heat flux 280632 W m^{-3} (2D simulation uses the third dimension as 1 m).

Membrane walls were replaced by a smooth surface, however, the thickness of the wall was set up to 5 mm. Since corrosion occurs on the surface of membrane walls the emissivity of walls was set up to 0.79 (corroded steel). Membrane walls also had temperature set up to the value of 255 °C, which was calculated by balance calculation. Inside the membrane walls, there is a vapour-liquid mixture (10.2 wt. % of steam).

The cooling effect of steam flow inside the tube was simulated by inner temperature of the tube. This temperature was calculated using thermal hydraulic calculations of the superheater.

Temperatures and velocities of flue gasses were crucial boundary conditions for each simulation. Those boundary conditions were applied along the top part of the model. The graph (Figure 4) shows used temperature profile for each domain.

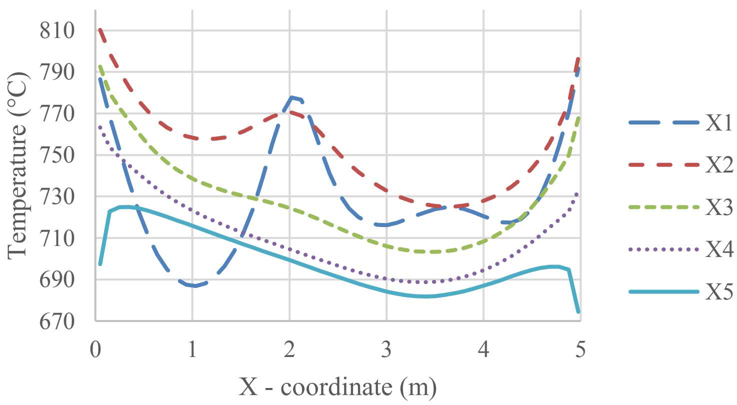

Figure 4. Temperature load for each cut of the superheater.

The velocity magnitude (shown in Figure 5) for each cut also differs. For simulation, only Y and Z components of velocity were used.

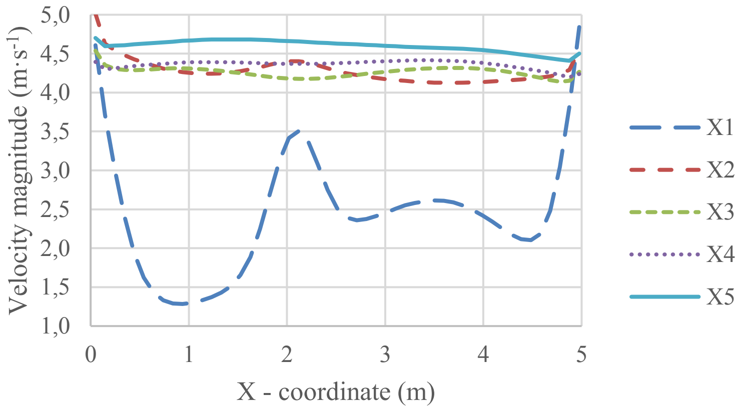

Figure 5. Velocity magnitude for each cut of the superheater.

3.3. Influence of simplification

The simulation was simplified to 2D problem therefore just two components of velocity were used (Y and Z components). Neglecting X-component of velocity boundary condition leads to inaccuracy which is shown in Figure 6. Inaccuracy is evaluated as a percent ratio of velocity X-component to velocity magnitude. Deviation (Table 1) for cuts X5, X4 a X3 is not that huge and can be neglected however for cut X2 it is a bit higher and the biggest is in the cut X1. Since the deviation in cuts X2 and X1 is quite big, it was necessary to evaluate its effect on heat transfer to the tube. It was performed by evaluating the effect on heat transfer coefficient using Nusselt number for tube bundle.

Table 1. Influence of velocity X-component neglection on the heat transfer coefficient.

Cut nr.		X1	X2	X3	X4	X5
Inaccuracy *v*	(%)	66.1	28.4	17.3	11.1	3.6
Inaccuracy α	(%)	45.05	17.25	9.76	6.08	1.85

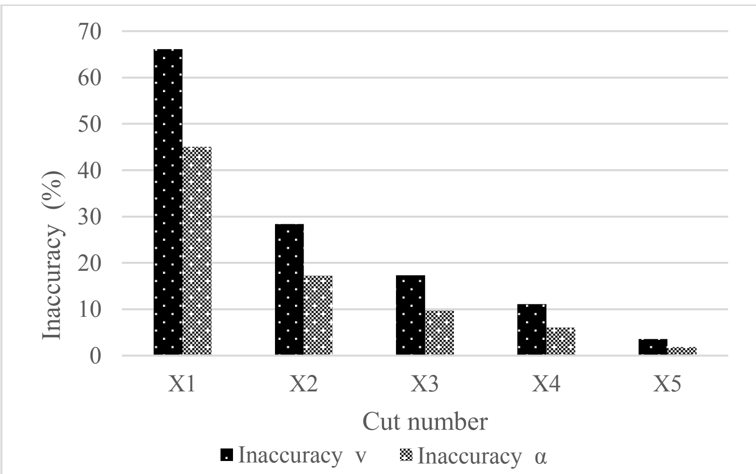

Figure 6. Graph of inaccuracy caused by neglecting X-component of velocity and its influence on the heat transfer coefficient for each cut of the domain.

As can be seen, the influence of neglecting X-component of velocity at cut X1 on the heat transfer coefficient is significant. Therefore, the cut X1 was not simulated (cut X1 is not a prerequisite for a critical area as soon as this part of the superheater is located right behind the membrane wall thus the flue gas flow is lower). All the other cuts were simulated.

4. Tube temperature and residual creep life

Four simulations of cuts X2, X3, X4 and X5 were performed. Tube temperature was evaluated and used for creep life estimation.

4.1. Tube temperature

Tube temperature on the outside was evaluated for each tube. The top part of the tube is the hottest (as can be seen in Figure 7), therefore there is the highest probability of temperature related damage. On the Figure 7 there are only top three rows of cut X5 since the temperature on the other tubes will be a bit lower due to the cooling effect caused by steam flow inside the tubes.

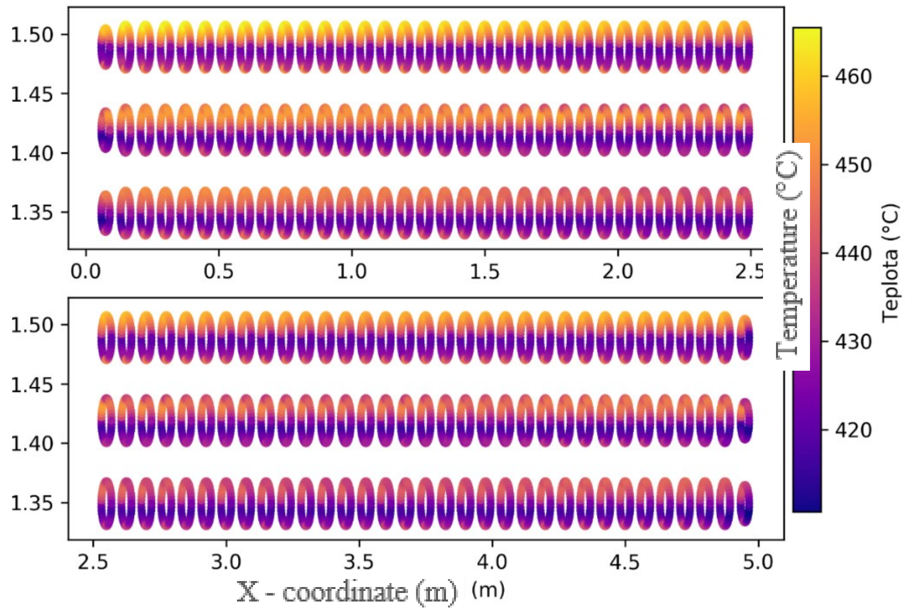

Figure 7. Surface temperatures on top three rows of tube bundle for cut X5 (left part of superheater at the top, right part at the bottom, fluid flow from the top).

For each cut, a tube with the highest temperature was selected for conservative residual creep life estimation. For X5 cut it is tube number 13 with the maximum temperature of 465.5 °C. For X4 cut it is tube number 1 with the maximum temperature of 466.6 °C. For X3 cut it is tube number 1 with the maximum temperature of 469.6 °C. For X2 cut it is tube number 1 with the maximum temperature of 470.3 °C. Based on those results it is obvious, that tube number 1 located in the first row of tube bundle has the highest surface temperature and therefore it will be the most susceptible to temperature related damage.

4.2. Residual creep life

Temperature-related damage may cause short-term or long-term overheating. In this case, the maximal tube temperature is 470.3 °C does not exceed critical transformation temperature of the material (843 °C), therefore short-term overheating probably will not occur. Maximal tube temperature is also lower than designed material temperature (540 °C) thus also long-term overheating probably will not occur.

Higher temperature may also lead to creep. Estimated creep life was calculated according to standard ČSN EN 12952-4 [10]. Results for the tubes with the highest temperature can be seen in Table 2. It is obvious, based on those results, that creep will probably not occur in this superheater either.

Table 2. Creep life expectancy of the most heavily loaded superheater tubes for each cut.

Cut no.		X2	X3	X4	X5
Tube no.		1	1	1	13
Life exp.	(h)	$1.22 \cdot 10^7$	$1.3 \cdot 10^7$	$1.69 \cdot 10^7$	$1.88 \cdot 10^7$
Life exp.	(years)	1394	1484	1929	2148

5. Conclusion

Superheaters are one of the most often parts of boiler where temperature related damage occurs. To evaluate this kind of damage and estimate residual life it is necessary to know the surface temperature of the tubes. Complex 3D simulations using CFD are often time-consuming and therefore some kind of simplification is needed. In this paper, five 2D cuts through the domain were used. This, however, led to inaccuracy because of neglecting of X-component of velocity. The inaccuracy was evaluated and based on results one of the cuts was not evaluated due to severe error in heat transfer coefficient. Maximal tube surface temperatures were calculated and the most critical tubes were selected for creep evaluation. The results show that the most exposed part of the superheater has the creep life expectancy of 1394 years, therefore, the creep damage should not be an issue under the current operating conditions. Newertheless the possibility of tempareture and life-time estimation has been shown. The method was presented and may be used for similar cases, where operational conditions might be severe.

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Acknowledgments
The authors sincerely thank for the financial support given by the Ministry of Education, Youth and Sports of the Czech Republic under the standard specific research project FSI-S-17-4526.