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Research paper

# Artificial Neural Networks model for predicting wall temperature of supercritical boilers

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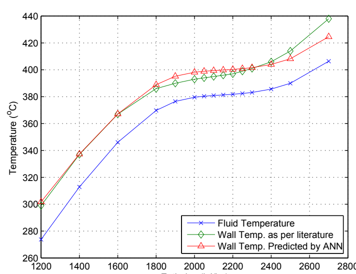
## HIGHLIGHTS

- Metal temperature is to be known at boiler design stage for material selection.
- Experimental metal temperature data collected at supercritical water conditions.
- ANN model developed using experimental data for metal temperature prediction.
- 100% agreement at ±7 °C deviation for experimental data.
- 97.22% agreement at ±10 °C deviation for literature data.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Prediction of wall temperature for the range of operating conditions and selecting appropriate material for water-wall tubes, cooled by turbulent water/steam with drastic changes in property, is important in boiler design. An analytical route of predicting the wall temperature for such flow conditions is not reliable. Empirical correlations of non-dimensional numbers, based on experimental data, are used for predicting wall temperatures of turbulent flow with abrupt changes in fluid properties. BHEL has conducted many experiments with supercritical water/steam and developed Artificial Neural Network (ANN) based wall temperature prediction model. This model predicts wall temperature using the given inputs of fluid pressure, fluid temperature, product of mass flux and diameter, and heat flux. The model has prediction accuracy of 100% for the experimental data and 81.94% for the literature data at a deviation level of ±7 °C. This ANN model is useful for predicting wall temperatures of supercritical boilers operating in the tested range of parameters.



## 1. Introduction

With the growing demand in energy, increased awareness about the environment and the increasing cost of energy, the design and construction of steam generators needs focused research and development to increase efficiency, reduce emissions and avoid failures of steam generators. Increasing the operating steam parameters of a power plant is a step towards which several boiler manufacturers are working in order to increase cycle efficiency, reduce emissions and reduce generation cost. Many thermal power plants with supercritical steam parameters are in operation and to

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go forward, research activities are in-progress for advanced ultra-supercritical steam parameters. In the supercritical power generation cycle, parameters with live steam pressure as high as 300 bar and live steam temperatures as high as 620 °C are used at present and developmental works are going on for adopting 350 bar/700 °C/720 °C cycle.

As a step towards understanding heat transfer at supercritical regimes of water/steam in detail, BHEL, Tiruchirappalli plant has established a heat transfer test facility at its complex. This facility could be used to simulate and study heat transfer under subcritical and supercritical conditions of water/steam as a working medium. Furthermore, this facility has been designed in such a way that tests with tubes of any orientation, any internal profile and any angle of circumferential heating could be carried out. The testing capabilities are the state of the art and can meet even the testing requirements of advanced ultra supercritical steam parameter range upto a pressure and temperature combination of 400 bar and 700 °C. This facility with an investment of over *Rs*. 100 million (approximately 2 million US dollars) has been recently commissioned and many tests with smooth internal profiled vertical tube test section have been carried out.

This paper presents the details of an ANN based inner-wall temperature prediction model developed using the data collected from the above mentioned test facility. In our approach, we reduce the number of dependent parameters to four by taking the product of mass flux and tube inner diameter as a single variable replacing the two independent terms of mass flux and tube inner diameter, since it is the factor that simulates Reynolds number whenever there is a variation in tube diameters between the prototype and the model. In the supercritical test facility, water, the same working fluid of the prototype boiler, has been used as a working medium. Hence, the influencing experimental parameters of pressure, temperature or enthalpy, heat flux, the product of mass flux and inner diameter and corresponding inner wall temperatures were taken as input for ANN model development with an aim to predict the inner wall temperature for the given input parameters.

## 2. A description of the test facility

Fig. 1 shows the scheme of the test facility and Fig. 2 shows the photographic view of the same. The essential component of the test facility is the test section which simulates the single tube conditions of the desired heat exchanger component of interest to us. It is electrically heated with a DC supply to provide the desired heat flux. All other components prepare the fluid to the required inlet conditions of the test section and dissipate the excess heat to the ambient. The major circuits and systems of the plant are

1. Feed water preparation, loading and pressuring circuit
2. High pressure main circuit (a closed loop)
3. Low pressure cooling water circuit (a closed loop)
4. Electrical, instrumentation, data acquisition and controls

The materials, heat exchangers, heaters, pumps and power supplies of this test loop have been selected such a way that testing under the following maximum test parameters are achievable:

- Maximum pressure: 400 bar
- Maximum temperature: 700 °C
- Maximum heat flux: 1000 kW/$m^2$
- Maximum boiler mass flux:
  - 8500 kg/$m^2$s (for 8.2 mm ID tube)
  - 3500 kg/$m^2$s (for 20 mm ID tube)

The test section is highly instrumented for tube wall temperature measurement. Instrumentation for measuring fluid flow, pressure and temperature at the inlet and outlet of the test section have also been provided. All the instrumentation and controls have been linked to the centralized state of the art Data Acquisition and Control system which is capable of capturing ten scans per second for all parameters. Operation and control of all equipment, valves and power supply are possible from the control room.

### 2.1. Experimental observations

Steady state experiments were conducted in the test facility with a smooth, 8.2 mm ID, vertical, 360° heated, SS tube under the following operating parameter range and data were collected.

- Water/Steam pressure (bar (*a*)): 219–401
- Water/Steam Temperature/enthalpy: 75–608 (°C)/336–3545 (kJ/kg)
- Heat flux (kW/$m^2$): 48.5–290
- The Product of mass flux and diameter (kg/ms): 17–42.4
- Mass flux (kg/$m^2$s): 2083–5170

For the given steady state parameters, the outer wall temperatures were measured and the corresponding inner wall temperatures were calculated.

## 3. Approach for model development

### 3.1. The conventional approach for predicting inner-wall temperature

In the conventional approach, for predicting metal temperature for complex turbulent heat transfer, experiments are conducted for the desired range and a combination of the influencing parameters like fluid pressure, temperature, mass flux and heat flux conditions and the metal temperatures at each combination of parameters are measured in an experimental set up. Experimental Nusselt number is calculated based on measured heat flux and the difference between inner-wall and fluid temperatures. The non-dimensional Reynolds and Prandtl numbers for the corresponding fluid parameters and flow conditions are calculated. An empirical correlation relating experimental Nusselt number and corresponding fluid Reynolds and Prandtl numbers is developed. This empirical correlation is used for calculating Nusselt number and heat transfer coefficient and further for predicting metal temperature for the given conditions. This process involves data reduction and a lot of calculations in arriving at a correlation from experiments and the possibilities for inaccuracies are more in this process.

There are several empirical formulaé derived from experiments relating non-dimensional numbers of fluid to compute the inner-wall temperature. Each one of these empirical formulaé may be suitable for one particular range of operating parameter. Further, these have been developed based on the linearization assumptions.

### 3.2. Simplified approach

The conventional approach is very useful when experiments are conducted with some modelling fluid and the prediction equations are used for the same fluid or for some other fluid. However, when the same prototype fluid is used in the experiments, the conventional non-dimensional route may be avoided and a simple direct relationship for the inner-wall temperature with operational parameters shall be established and used for prediction purpose. Similar approach is followed by Loewenberg et al. [1] where a look-up table has been developed based on experimental data to predict