Numerical Analysis of Flow Instability in the Water Wall of a Supercritical CFB Boiler with Annular Furnace Postprint

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Abstract

Supersonic cavity flows are characterized by compression and expansion waves, shear layer, and oscillations inside the cavity. For decades, investigations into cavity flows have been conducted, mostly with flows at zero pressure gradient entering the cavity in straight walls. Since cavity flows on curved walls exert centrifugal force, the features of these flows are likely to differ from those of straight wall flows. The aim of the present work is to study the flow physics of a cavity that is cut out on a curved wall. Steady and unsteady numerical simulations were carried out for supersonic flow through curved channels over the cavity with L/H = 1. A straight channel flow was also analyzed which serves as the base model. The velocity gradient along the width of the channel was observed to increase with increasing the channel curvature for both concave and convex channels. The pressure on the cavity floor increases with the increase in channel curvature for concave channels and decreases for convex channels. Moreover, unsteady flow characteristics are more dependent on channel curvature under supersonic free stream conditions.

Full Text

Preamble

To expand the study on flow instability in supercritical circulating fluidized bed (CFB) boilers, this paper presents a new numerical computational model that considers the heat storage of tube wall metal. The lumped parameter method is proposed for wall temperature calculation, and the single-channel model is adopted for flow instability analysis. Based on the time-domain method, a new numerical computational program suitable for analyzing flow instability in the water wall of supercritical CFB boilers with annular furnace was established. To verify the code, calculation results were compared with commercial software

data. These comparisons proved that the new code is reasonable and accurate for practical engineering applications in flow instability analysis. Using this new program, the flow instability of a supercritical CFB boiler with annular furnace was simulated via the time-domain method. When a 1.2 times heat load disturbance was applied to the loop, results showed that the inlet flow rate, outlet flow rate, and wall temperature fluctuated with time but eventually remained at constant values, suggesting that the hydrodynamic flow was stable. The results also demonstrated that when heat storage is considered, the flow in the water wall returns to a stable state more easily than when heat storage is neglected.

Keywords: supercritical CFB with annular furnace; heat storage; flow instability; wall temperature; numerical

Introduction

Circulating fluidized bed (CFB) combustion technology offers advantages including low NOx emissions, wide fuel adaptability, high combustion efficiency, and low pollution control costs, leading to widespread application in electric power, petroleum, chemical, and waste disposal industries. Compared with subcritical CFB boilers, supercritical CFB boilers operate at higher parameters, where the fluid in tubes is likely to reach supercritical state at high loads or remain in two-phase state at lower loads. To ensure safe and reliable operation, film boiling (DNB) must be prevented, and tube temperatures must remain within safe ranges after dryout (DRYOUT).

Over recent decades, flow instability has drawn widespread concern regarding the design and operation of various heat transfer equipment, including nuclear reactors, refrigeration plants, and boilers. Flow instability may cause wall temperature oscillations, leading to tube fatigue damage and heat transfer deterioration [1]. Thus, investigations into flow instability are essential. Since 1938, domestic and foreign scholars have conducted extensive and in-depth studies on two-phase flow instability [2-16]. However, few studies have addressed flow instability considering the heat storage of tube wall metal in boilers. Since furnace heat flux density is influenced by metal heat storage, the dynamic characteristics of the furnace are also affected, making it necessary to study hydrodynamic flow instability in boilers while considering tube wall metal heat storage. This paper establishes a numerical computational model that incorporates metal heat storage and is suitable for flow instability analysis and wall temperature calculation using the lumped parameter method. Based on Fortran, the single-channel model and time-domain method are adopted.

To provide guidance for boiler design and operation, the loop most susceptible to flow instability in the water wall was selected as the research object.

Mathematical Model

Generally, two main approaches exist for solving the governing equations of mass, momentum, and energy. The first is the frequency-domain method, which converts linearized equations to transfer functions via Laplace transform [17-23]. However, the frequency-domain method cannot effectively solve nonlinear problems. The second is the time-domain method, which conserves the nonlinear information of the original equations through numerical discretization and integration [24-28]. The present code employs the time-domain method. Tube wall temperature can be calculated using either the lumped parameter method or the distributed parameter method; this paper uses the lumped parameter method for wall temperature analysis and calculation.

Nomenclature

- A: inner cross-section area, m^2
- d: inner diameter, m
- f: friction factor
- L: axial length, m
- Δz: space step, m
- g: gravity, m/s^2
- h: specific enthalpy, J/kg
- i: space index
- j: time index
- ρ: density, kg/m^3
- θ: angle of flow direction with respect to horizontal plane, radian
- δ: dimensional Dirac delta function, m^{-1}
- α: convective heat transfer coefficient, W/m$^2 \cdot$ K
- ξ: pressure drop coefficient
- L_{total}: total length of channel, m
- M: mass flow rate, kg/s
- n: total number of control volumes
- P: pressure, Pa
- ΔP: pressure drop from inlet to outlet, Pa
- q: linear power density, W/m
- S_i: internal surface area per unit length
- c: specific heat, W/m$^2 \cdot$ K
- m: mass per unit length, kg/m
- t: temperature, °C
- Δt: time step, s
- in: inlet
- out: outlet
- $local$: local
- $inner$: inner
- $fluid$: fluid
- Superscripts:

- 0: the initial steady value
- *old*: the old time value
- *new*: the new time value

Basic Assumptions

For analyzing boiler flow instability, the following assumptions are proposed: 1. A one-dimensional model is employed considering compressibility and thermal expansion. 2. Water temperature and velocity are uniformly distributed in the cross-section, and water flows only along the axial direction. 3. Only heat transfer in the radial direction is considered. 4. Effects of kinetic energy, potential energy, and viscous dissipation on the energy equation are ignored.

Transient Equations for Supercritical Fluid

Supercritical water has no phase change and can be regarded as single-phase fluid. The basic governing equations for supercritical water are the same as those for the homogeneous flow model.

The mass equation is:
The momentum equation is:
The energy equation is:
The state equation is:
The metal heat storage equation is:
The heat transfer equation of working fluid side is:

Numerical Calculation Method

Discretization

As shown in [Figure 1: see original paper], the channel is divided into several control volumes from inlet to outlet with equal length Δz. The non-staggered grid method is used for dividing the control volume of the flow channel. Fluid physical state parameters such as mass flow rate, pressure, density, temperature, and enthalpy are located at the center of the control volume. Discretization of the governing equations employs a first-order upwind scheme in space and an implicit scheme in time. According to the first-order upwind scheme, physical state parameters at the junction are equal to those of the adjacent upstream control volume. Integration of the governing equations on each control volume yields the following equations:

Mass equation:
Momentum equation:
Energy equation:
State equation:
Metal heat storage equation:
Heat transfer equation of working fluid side:
Facilitated heat transfer equation:

Boundary Conditions

For the single-channel model, the boundary conditions are: 1. Inlet enthalpy h_{in} is given and constant. 2. Inlet pressure P_{in} is given and constant. 3. Pressure drop from inlet to outlet ΔP is constant.

Solution Method

A summary of the solution method is shown in [Figure 2: see original paper]. The initial values of P, M, h, ρ, t_w, and t_f are first computed. After that, a small perturbation of heat flux is imposed on the steady state, and steps are repeated to calculate the transient values at the next time step level. The equation of metal heat storage is combined with the heat transfer equation, and the system is solved for each control volume. The inlet mass flow rate is assumed, and the calculation proceeds from inlet to outlet. For each control volume, the mass, momentum, and energy equations are solved sequentially, with the state equation used to update density until convergence is achieved. After completing the outlet calculation, the outlet pressure is obtained. If the relative difference meets the precision requirement, the assumption of inlet mass flow rate is correct, and the solution proceeds to the next time step. If not, a chord secant method is used to iterate until the relative difference is satisfied. The solution method for steady-state equations is similar to the transient equations and is not detailed here.

Validation

To validate the present code, calculation results obtained by the numerical code were compared with simulation results from Dynastab software. Dynastab is commercial software developed by Siemens Ltd. for simulating hydrodynamic flow, aimed at providing guidance for boiler design and operation. In this paper, the geometric structure and thermal parameters are identical to those used in Dynastab software for practical engineering application of a 600 MW supercritical W-shaped boiler.

Initial calculating parameters are shown in . To simulate flow instability precisely and calculate wall temperature within a smaller error range, factors including inclined angle, heat distribution, and tube type are considered. Comparison results are shown in [Figure 3: see original paper], [Figure 4: see original paper], and [Figure 5: see original paper].

[Figure 3: see original paper] shows that the wave curve of inlet flow versus time derived from the present program is consistent with the curve derived from Dynastab, indicating that the method of this paper has certain reliability for simulating flow instability of supercritical water. According to [Figure 4: see original paper], the relative error of fluid temperature and wall temperature between the program and Dynastab is 0.04% and 0.2%, respectively, proving that the present program reasonably simulates fluid temperature and wall temperature within error limits.

[Figure 5: see original paper] shows that the wave curve of inlet flow versus time in the case of considering heat storage of tube wall metal restores to the initial state more quickly than flow fluctuation without considering heat storage. This means that flow in the water wall is more stable with heat storage, indicating that metal heat storage influences the dynamic characteristics of the furnace. Therefore, it is necessary to consider metal heat storage when analyzing boiler flow instability.

Analysis of Flow Instability in Supercritical CFB Boiler with Annular Furnace

Annular Furnace Structure

[Figure 6: see original paper] shows the simple structure of the annular furnace. The furnace is divided into inner and outer rings arranged in parallel. Three groups of cyclone separators are installed on the front wall of the outer ring, with the same arrangement on the back wall. This structure allows more water cooling walls to be arranged to obtain sufficient heat exchange area while reducing furnace height and circulating pump power consumption.

In this paper, the sixth loop of the front wall was selected as the study object. Initial calculating parameters are expressed in . The loop uses vertical smooth tubes with low mass flow, with inner and outer diameters of 19 mm and 32 mm, respectively, and a length of 55.6026 m.

[Figure 7: see original paper] and [Figure 8: see original paper] show the pipeline structure and heat load distribution. The heat load distribution along the furnace height is non-uniform. According to the characteristics of heat flux distribution along furnace height, the water wall is divided into more sections where heat flux experiences sharp changes and fewer sections where heat flux changes gently [29]. This approach fully considers the non-uniform distribution of heat flux in calculations. In this paper, the water wall is first divided into 33 sections, with each section further divided into equal lengths equivalent to the space step size Δz. [Figure 7: see original paper] shows the length of each section where heat flux is uniformly distributed. With a spatial grid length of approximately 0.1 m, the loop can be divided into 560 segments. Two constants are used as the time step Δt to ensure independence between time and space steps: from 0 to 1 s, the time step is 0.1 s; from 1 to 500 s, the time step is 1.0 s.

Dynamic Characteristics of Furnace

Dynamic instability of the furnace occurs when heat flux density changes for various reasons. The inlet and outlet of the loop form a reciprocating cycle mode where flow rates increase or decrease when dynamic instability occurs. If the resistance characteristics of the furnace and flow fluctuations reach a certain resonance, the flow fluctuations will remain in a stable state of oscillation without decay. In some cases, frequent tube temperature changes lead to pipe fatigue failure, which is not conducive to safe boiler operation and should be avoided.

When considering heat storage of tube metal and applying 1.2 times heat load disturbance to the sixth loop, the fluctuation of inlet and outlet flow rates versus time is shown in [Figure 9: see original paper]. It can be seen that inlet and outlet flow rates fluctuated in reversed phase: when inlet flow rate increased, outlet flow rate decreased, and vice versa. The amplitude of inlet and outlet flow rates gradually decreased with time, eventually equalizing and restoring to a steady state, suggesting that the flow condition was stable.

Temperature Analysis

Without heat load disturbance, the sixth loop at steady state had an inlet pressure of 10.16 MPa, inlet enthalpy of 1343.097 kJ/kg, and inlet flow rate of 0.065 kg/s. Based on this steady state, 1.2 times heat load disturbance was applied to the sixth loop. Simulation results are as follows:

[Figure 10: see original paper] shows the average fluid temperature at steady state and wall temperature in three cases. At 4.1 s, heat load reached maximum value while inlet flow rate dropped to minimum; at 13.1 s, inlet flow rate reached maximum value while heat load recovered to initial value. In [Figure 10: see original paper], the inflection point of each curve represents the phase transition point. Taking steady state as an example, two inflection points exist in the average temperature distribution curve: one in the 8th section and another in the 26th section, indicating that fluid in the first seven sections is in single-phase liquid state, fluid in sections 8-26 is in the two-phase region, and fluid in remaining sections is superheated steam.

From 1 to 500 s, the maximum tube wall temperature was 435°C, which is within the allowable range, so boiler operation is safe and reliable. [Figure 11: see original paper] and [Figure 12: see original paper] exhibit temperature fluctuations of the 55th control volume (single-phase region) and the 275th control volume (two-phase region). Both fluid temperature and wall temperature fluctuated with time but eventually remained at constant values. The wall temperature in the single-phase liquid zone was only 1.5°C higher than fluid temperature, while the temperature difference between wall and fluid in the two-phase region was 2.8°C.

Conclusion

This study proposes a general model considering heat storage of tube wall metal. To further expand research on supercritical flow instability in boilers, a numerical program applying the time-domain method was developed. The program can simulate flow instability in boilers with various geometric structures and thermal parameters and calculate tube wall temperature. Comparisons with Dynastab numerical calculation data show that the present model is suitable and adequate for analyzing flow instability in water walls and calculating tube wall temperature, making it applicable for practical engineering use.

Numerical analysis of flow instability in the water wall of a supercritical CFB boiler with annular furnace shows that when applying 1.2 times heat load disturbance to the loop, inlet and outlet flow rates exhibited reversed-phase fluctuations but eventually equalized, while wall temperature fluctuated with time before remaining at constant values, suggesting stable flow conditions. Additionally, results showed that when heat storage is considered, flow in the water wall returns to stable state more easily than without considering heat storage.

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Note: Figure translations are in progress. See original paper for figures.