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Research Article

Mathematical Simulation of Tube Rack Thermal Shelding in A Tube Plate of Fire-Tube Boiler

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Abstract

The results of investigation of hydro- and thermodynamic processes in some parts of a fire-tube hot-water boiler are presented. The studies have been carried out using modern simulation techniques of fluid dynamics. A number of factors that can improve boiler reliability are revealed on the basis of numerical experiment results.

Keywords: *Fire-tube boiler, numerical experiment, flow parameters, thermal state, thermal shielding, compressibility, turbulence.*

Introduction

Purposes of the research

Reliability and service life of turbine – powered boilers are largely determined by operating characteristics of attachment points of heat exchanger tubes and tube sheets.

During the study of hydro and thermodynamic processes in working elements of a turbine – powered water boiler KUVI by the methods of computer simulation, it has been revealed that in attachment points of tubes, areas of local overheating in the weld area appear (Gainov A.A, 2011). A number of adverse factors such as non-optimal geometric parameters of an attachment point (thickness of a tube sheet, arrangement pitch of the tubes), unequal distribution of a gas flow over the front of a tube sheet, presence of crust and other deposits from the water chamber cavity etc. leads to the development of this process.

The consequence of local overheating is leakage of attachment points of heat exchanger tubes and tube sheets and quick breakdown of turbine – powered boilers.

One of the most effective methods of protection against the flow of hot gases to boiler's elements, including a tube sheet is thermal isolation. The preliminary work allows to offer several constructions of thermal protection elements, which are based on the use of thermal isolation material of a certain thickness.

Taking into account unequal distribution of gas flow over the front of a tube sheet, which may lead to appearing of local hot spots of overheating on tube walls in the area of rolling and welding, it has been proposed to use aerodynamically profiled protective pistons in combination with thermal isolation material. The aerodynamic shape of pistons has been developed based on the results of the mathematical modeling (Gainov A.A, 2011), in which a gap of the gas flow on the areas with sharp turns has been detected. It is known from gas dynamic theory that the suppression of flow gaps is possible in tapering channels, moreover, a smooth tapering channel can reduce gas dynamic losses at the inlet of tubes. Since a piston inevitably leads to narrowing of the channel entrance and, respectively, to the increase of losses in the tapering part, an inlet part of a piston is designed as a diffuser, its opening angle guarantees a steady flotation at a symmetric flow. The outlet part ought to provide the recovery of hydraulic drop.

Considering the given above, the following tasks ought to be investigated:

–Determination of the effect of thermal isolation thickness and protective pistons on the thermal state of attachment points;
–Determination of the effect of pistons on aerodynamic characteristics of the gas flow.

Description of a boiler–utilizer

A horizontal intensified turbine – powered water boiler –utilizer KUVI is intended for utilization heat of exhaust gases of internal combustion engines. An operating temperature of hot gases at the entrance is up to 873 K, at the outlet is 393 – 423 K. As a heated coolant both water and ethylene glycol solutions with temperatures up to 388 K can be used.

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KUVI boilers are designed using a scheme of a cross – flow heat exchanger with a total contraflow. At that using gas one pass is provided and using liquid – from 3 to 8 passes.

For working in diesel marine power systems, as a material for all elements of boilers, corrosion – resistant steel 10X17H13M2T is used. For collaboration with gas piston generators, all parts are made of steel 08H18N9T, 12X18H9T (or analogical AISI 321).

A conical front cover of all boilers contains a system of diffusers – gas distributors at the entrance to the tube bundle. This ensures uniform distribution of coolant, local overheating excepted and generally the thermal efficiency of boilers increases.

On all boilers KUVI weldless or electrical welded tubes with diameter from 16 to 25 mm and with wall thickness from 1 mm to 1.5 are used. The tubes are profiled for heat transfer intensification. Due to small diameter, dense packaging and profiling of the tubes, very high weight and size characteristics of boilers KUVI have been achieved (Valiulin S.N, 2011).

Mathematical statement of task

The investigation of the influence of thermal isolation and protective pistons on the thermal state of working elements of a gas – tube water boiler – utilizer with forced circulation is made by the methods of computational experiment.

The settlement area is a half of a cell of a gas – tube boiler–utilizer KUVI (figure 2). In the simulation, the following assumptions have been accepted:

–A welding seam connecting a tube with a tube sheet is formed from the material of a tube sheet and has the same thermal characteristics;
–Thermal characteristics of coolants in a calculated point are accepted by average integral values of temperature and pressure;
–Water pressure in the cavity provides absence of phase transition (evaporation) in a range of calculated temperatures.

In area 1 of the calculated field gas locates, in area 2 – water. Movement of the fluids – of water and gas – and heat transfer processes in a boiler are described by the following system of equations:

$$\frac{\partial \rho_i}{\partial t} + \nabla(\rho_i \vec{V}_i) = 0 \quad (1)$$

$$\frac{\partial(\rho_i \vec{V}_i)}{\partial t} + \nabla\left(\rho_i \vec{V}_i \otimes \vec{V}_i\right) = -\nabla p + \nabla \tau_i \quad (2)$$

$$\frac{\partial(\rho_i c_{pi} T)}{\partial t} + \nabla\left(\rho_i c_{pi} T \vec{V}_i\right) = \nabla(\lambda_{ie} \nabla T) + \nabla\left(\vec{V}_i \tau_i\right) + \frac{\partial p}{\partial t} \quad (3)$$

where i = 1 is related to fume, i = 2 – to water, i = 3 – to steel, i = 4 – to boiler scale, i = 5 – to thermal isolation material; p – absolute pressure, T – absolute temperature, ρ_i – density of a corresponding media, $p/\rho_1 = (c_{p1} - c_{v1})T$, ρ_2, ρ_3, ρ_4, ρ_5 – const, $\vec{V}_i$ – velocity vector of a corresponding media ($\vec{V}_3 = \vec{V}_4 = \vec{V}_5 = 0$), τ_i – stress tensor related to deformation velocities by the generalized Newton hypothesis $\tau_i = \mu_{ie}(\nabla\vec{V}_i + (\overline{\nabla}\vec{V}_i)^T - \frac{2}{3}\delta\nabla\cdot\vec{V}_i$, μ_{ie}, λ_{ie} – effective viscosity and thermal conductivity of mediums respectively, $\mu_{ie} = \mu_i + \mu_{it}$, $\lambda_{ie} = \lambda_i + \lambda_{it}$, μ_i, λ_i – laminar viscosity and thermal conductivity, μ_{it}, λ_{it} – turbulent (vortex) viscosity and thermal conductivity related to each other by the turbulent Prandtl number ($\mu_{3e} = \mu_{4e} = \mu_{5e} = 0$, $\lambda_{3t} = \lambda_{4t} = \lambda_{5t} = 0$) and defined by a chosen model of turbulence. The sign $\otimes$ in equation 2 and T in the note of τ_i define vectorial vector operations and vector transportation respectively.

Note that gas in the task is considered as compressible liquid and water as incompressible. The system of equations (1) – (3) closes by the transport SST Menter turbulence model (Bystrov U.A, 2005). This model is a combination of k – ω model (a more accurate description of the flows near walls) and k – ε model (simulation of the flows far away from solid boundaries). Considering the importance of the research of turbulence areas in near – wall regions (in particular, when a piston is injected into a pipe) in the task it is advisable to use the given model of turbulence.

For solid bodies, in this model it is tubes (region 3 on figure 2), a tube sheet (area 4 on figure 2), pistons (area 5 on figure 2), a layer of scum sediments in the annular gap between a tube and a tube sheet (area 6 on figure 2) and a layer of thermal isolating material (area 7 on figure 2), the heat conduction equation is solved.

The system of equations (1)–(3) should be completed by appropriate initial and boundary conditions. In the task the following boundary conditions are given:

1. On solid boundaries the usual for classical hydrodynamics slip condition is postulated. The case of "vanishing" viscosity is not considered in the task.
2. To inlet ABCD gas with velocity 6.2 m/s and with temperature 873 K is delivered.
3. To entrance boundary EHGF water with velocity 1 m/s and with temperature 353 K is delivered.
4. At exit boundaries M, N and IJKL zero excess pressure are prescribed. Note that exit boundary IJKL of the computational area is far away from the location of tubes to eliminate the influence of possible disturbances near the exit on the flow nature in the researched area around the tubes.
5. ACOILF - a plane of symmetry.

At start time, the temperature of the computational area is 353 K, in area 1 gas flow is given, in area 2 – water flow. The flow rates are coordinated with the corresponding velocities.

In the annular gap between a tube and a tube sheet matter with low thermal conductivity is prescribed, so-called scum.

Key aspects of the task solution

A grid model was built based on the grid generator Ansys ICEM CFD, the number of nodes in the grid during the calculations was about 900000, the solution produced in the gas hydrodynamics package Ansys CFX. In the package Ansys CFX the numerical solution of system (1) – (3) is based on the finite volume method (Bajan P.I, 1989).

The choice of the number of nodes in the grid model was implemented by the comparing of the preliminary calculations on grids with 500000, 900000 and 2 million nodes. The studies showed that optimal according to counting rate and accuracy of the results was a grid model, containing 900000 nodes. The task was solved on an eight – processor computational node with 16 GB of RAM. Parallelization of the task was carried out by the domain – splitting method. Under the above conditions, the solution took about a day.

The mathematical model includes five different environments-2 liquid (water, gas) and three solid mediums (steel, scam, thermal isolation material). Prescribed in the mathematical model thermal and transport properties of these mediums (Peire R,1986) (table 1) correspond to actual characteristics of the materials used in the boiler.

Results of the Modelling

1. The effect of thickness of an isolation layer on temperature distribution in a node.

Figure 3 shows temperature fields obtained from the results of two numerical experiments –modeling of working of a boiler element with a layer of isolation (a) and without (b).

The mathematical modeling confirms high efficiency of thermal isolation of a tube sheet in aid of thermal protection of an attachment point.

To establish acceptable thickness of an isolation layer in the work, the simulation process of a boiler for different thicknesses h (figure 4) – 2, 4, 6, 10 mm was carried out. Figure 4 shows temperature graphs at a constant thickness of a tube sheet for the studied values of h.

As seen from the figure, even with a thermal isolation layer in 2 mm the tube sheet is cooled to a suitable temperature in the area of attachment points upon condition of hermeticity of connections of isolating material with surfaces of the tube sheet and the piston (about 350 K).

2. Investigation of the influence of presence of pistons on the uniformity of gas flow.

Figure 5 shows streamlines of gas in a boiler element for cases of absence (figure 5, a) and presence (figure 5, b) of pistons at the entrance of tubes.

The mathematical modeling indicates elimination of a breakdown of a gas flow at the inlet to a tube during installation of pistons therein. Availability of pistons has a positive effect on uniformity of a flow and promotes elimination of vorticity in the wall – adjacent region of tubes (figure 6).

Note also that presence of pistons reduces overall resistance of the input area, which in turn reduces air resistance of a boiler (figure 7).

Results of the metallographic research of the samples of damaged areas of attachment points of tubes

In Alekseev NSTU the metallographic examination of the samples of attachment points of tubes from two different boilers was carried out. Figure 8 shows the photos of the studied samples. Thickness of a tube sheet of the first boiler was 20 mm (this boiler KUVI became a physical basis for the calculation model (Gainov A.A, 2011)). There is cracks in the boiler's walls (figure 8, a). The second boiler (figure 8, b) has thickness of a tube sheet 6 mm, it was equipped by thermal protection with pistons. Operation of the boiler and its following opening – up did not reveal any problems, as it was with the first boiler.

Location of the cracks in the studied samples fully corresponds to the picture of temperature distribution obtained in the mathematical experiment. Locations of the cracks are situated not in the weld zone but are displaced from it deep down along gas motion in the tube, which corresponds to the unfavorable area on figure 3.

It should be noted that the damaged tubes were arranged predominantly radially along the outer perimeter of the tube sheet, as well as in the places of previously plugged tubes that also serves to promote unsteadiness of gas flow at the inlet to the tubes.

Discovered at the opening – up of the boiler body deposits on the inner surface of the front tube sheet and the tubes influenced not only on the development of the cracks, but in addition certain locations of corrosive alkaline effects were discovered. Typically, main deposits are observed in high temperature zones. A rear tube sheet is one of those places.

The assumption that uneven distribution of gas over the area of a tube sheet may lead to local overheating has confirmed. The presence of deposits, the locations of corrosion and the cracks indicate that even a small temperature excess in the studied area is an unfavorable factor.

Conclusions

In this work the mathematical model of the processes in an attachment point connecting tubes with a tube sheet has been established and studied. Based on the assumptions and limitations bringing their characteristics to real physical, the adverse factors were revealed, affecting operational reliability of gas – tube boilers.

According to the results of the mathematical modeling it has been established:

1. When using a special form of pistons, a break – down of a gas flow at the tube inlet is liquidated. Thus, losses of a gas flow are minimal, and therefore, there is no significant increase of air drag in a boiler.
2. By providing isolation of a tube sheet, an attachment point of tubes is isolated from high temperatures.
3. The study has revealed the possibility of reducing of thickness of an isolation layer, and according to the simulation results it has been concluded that it is possible to its decrease to 2 mm providing airtight connections of isolating material with the surfaces of a tube sheet and pistons.
4. The mathematical modeling results are confirmed by the laboratory tests of the samples, and it proves practical importance of modeling not only for design, but also for revealing the causes of failures in operating boilers.

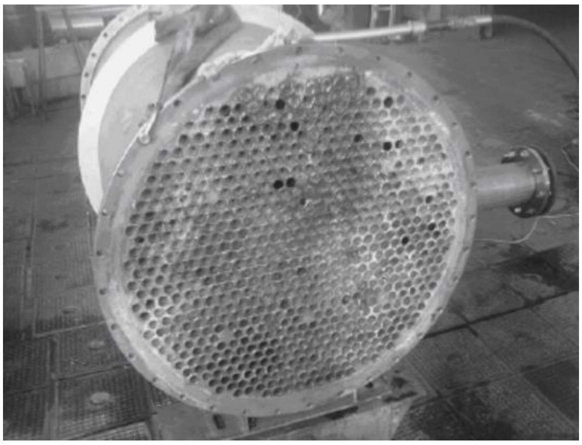


Fig.1 Boiler–utilizer KUVI

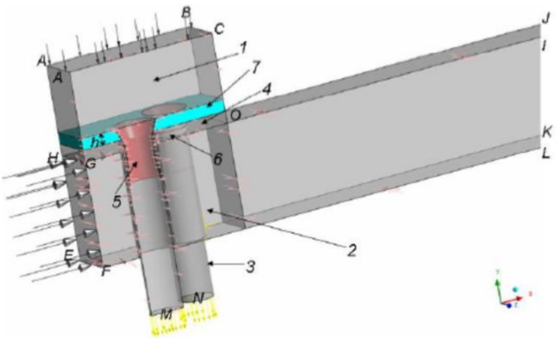
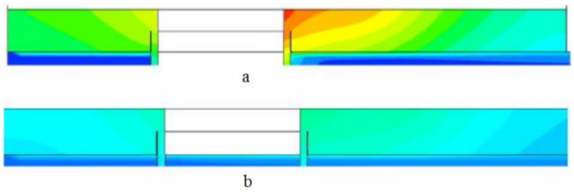


Fig. 2 Calculation area of the task



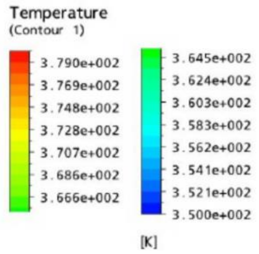


Fig.3 Thermal field in section of a tube sheet

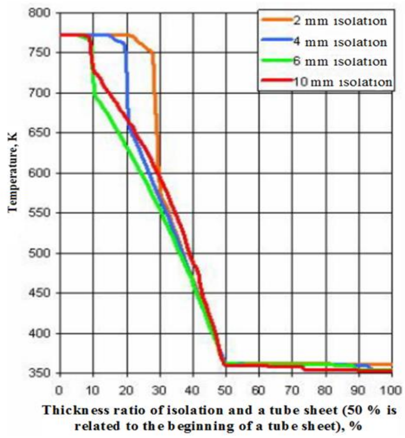


Fig.4 Graphs of temperatures at constant thickness of a tube sheet

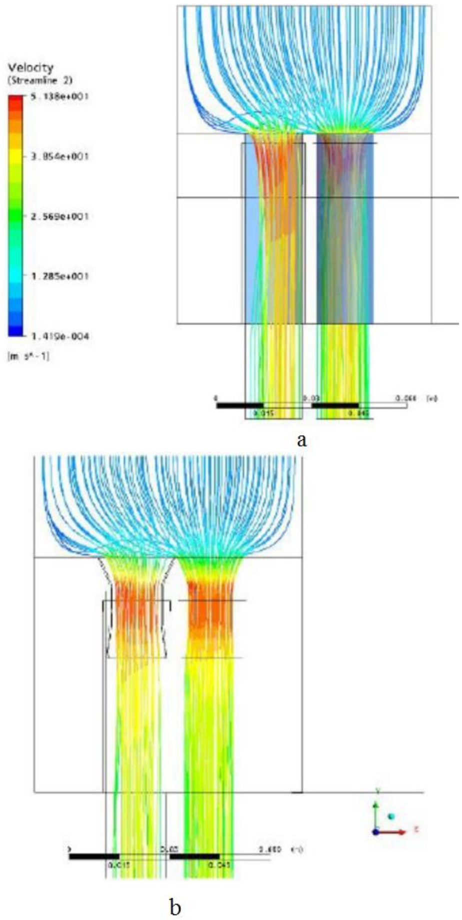
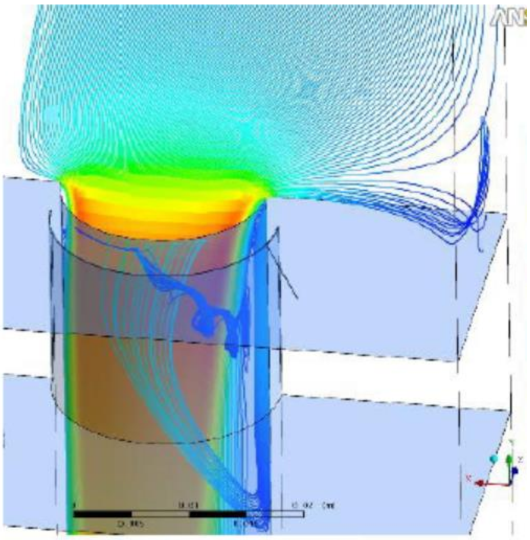
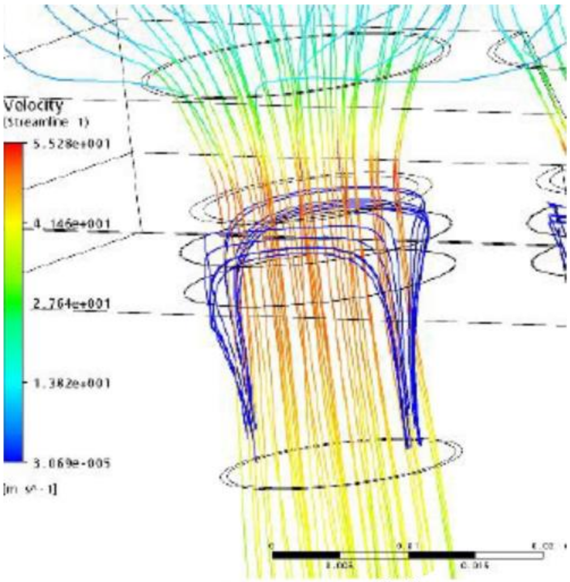


Fig.5 Gas streamlines in the area of a boiler



Absence of pistons



Presence of pistons

Fig.6 Streamlines in the area of tubes' walls

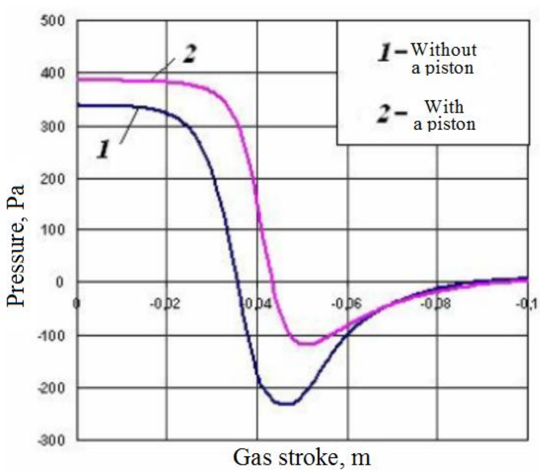
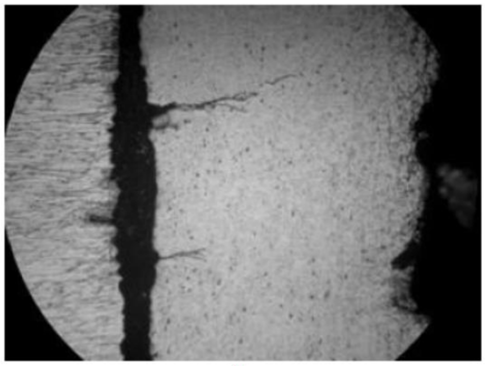


Fig.7 Statistical gas pressure at the inlet to a tube



a

b

Fig.8 a) The first test sample (without isolation and pistons), cracks on the tube's wall, scum deposits, corrosion of the tube sheet; b) The second test sample (with isolation and pistons), there is no deposits or cracks on the tube's wall.Table 1

Table:1 Material characteristics used in the boiler

Material	Density, kg/m^3	Specific heat, J/kg·K	Viscosity Pa·sec	Thermal conductivity, Watt/m·K
Water	950	4220	0.00025 8	0.68
Gas	28.96	1185	3.5e-0.5	0.0656
Steel	7854	434	-	60.5 -0.02· ·(T-273[K]), where T - temperature
Scam	1500	700	-	0.1
Thermal isolation	200	900	-	0.04

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