Numerical Simulation of the Process of Combustion of a Stoichiometric Hydrogen-Oxygen Mixture in a Steam Generator

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Numerical methods are used to study the process of combustion of a stoichiometric hydrogen-oxygen mixture. The mathematical models were validated using experimental data. The combustion process is modelled in the three-dimensional unsteady formulation. With account of the recommendations of other authors, the turbulent flows are described in the paper using the standard $k$-$\varepsilon$ turbulence model. The Eddy Dissipation Model (EDM) is used to describe the process of combustion of the hydrogen-oxygen mixture. The description of the complex heat transfer between the gas, flame and walls in the paper accounts for radiant heat transfer by using the P1 model. The paper deals with combustion processes in a burner and a model steam generator. Numerical methods were used to evaluate the effect of inlet flow turbulisation, and the flow rate and the method of feeding extra water to the combustion chamber on the process of combustion of the stoichiometric hydrogen-oxygen mixture. The influence of the design and operating mode factors on the alteration of the flame-steam interface and on the flame extinguishing conditions were studied. The results obtained can be used in future in designing equipment that uses hydrogen as a fuel to increase nuclear power plant (NPP) manoeuvrability.

Introduction

Hydrogen is a promising eco-friendly fuel for power systems [1-3] and it has a significant potential (it can be used in direct firing, e.g., in burners and an internal combustion engine [1-10], and oxidized on the anode in fuel cells [11]).

The process of hydrogen combustion in oxygen excludes the formation of toxic components, and hydrogen can be used as a fuel in the auxiliary steam generator in a thermal or nuclear power plant [12-15].

The authors of the papers [16, 17] studied the kinetics of chemical reactions during the combustion of hydrogen-oxygen mixtures.
Publication [16] considers the formulation of a chemical reaction, and the mechanisms and the process of setting up chemical rate equations from stoichiometric data and elementary reaction rates.

The authors of [17] showed that an optimized hydrogen combustion mechanism provides the most suitable description of the ignition delay time and laminar flame speed, with this being in good agreement with experimental data.

Paper [18] dealt with optimisation of hydrogen combustion mechanisms and synthesis gas; the covariance matrix of the optimised parameters was calculated, and temperature-dependent uncertainty ranges were obtained for the rate coefficients of each of the optimised reactions.

Paper [19] performed a comparison and analysis of the performance of several hydrogen combustion mechanisms. An approach was considered to exclude those measurements that none of the mechanisms could reproduce within a predefined uncertainty.

An analysis of sensitivity coefficients was carried out to identify reactions and ranges of conditions that require more attention in the future development of hydrogen combustion models.

Paper [20] examined chemical modelling and its influence on the transition of combustion conditions from deflagration to detonation. It was shown that, in the case of hydrogen-air mixtures, the multi-step chemical description is far more restrictive than the single-step model when it comes to the necessary conditions for a hot spot to lead to detonation.

The authors of [21] used experimental and numerical methods for a slot burner to study the effect of enrichment with hydrogen and addition of steam on the speed of the laminar flame of preliminarily mixed methane and air. The results showed that enrichment with hydrogen increased the laminar combustion rate and the flame adiabatic temperature. The addition of steam to a methane-air mixture noticeably decreased the burning rate and the adiabatic flame temperature.

A specific feature of operation of thermal and nuclear power plants is their cyclic load period [22]. This calls to look for ways to increase their manoeuvrability by accumulating extra energy during slack hours and returning the accumulated energy during peak load hours [14, 15].

One of the ways of increasing the manoeuvrability of thermal and nuclear power plants is accumulating extra energy by separately generating hydrogen and oxygen using the water electrolysis method [23], followed by their storage in high-pressure cylinders and further combustion in an auxiliary steam generator installed, for instance, in the steam turbine intermediate pressure stage [14, 15].

It is known that hydrogen, as a fuel, as compared with other combustible gases, has a
number of significant advantages: a high combustion heat and rate, wide ignition concentration ranges and a low activation energy [14].

During combustion of the stoichiometric hydrogen-oxygen mixture, the temperature in the flame zone reaches 3,000 °C [14, 15], with superheated steam being generated in the steam generator flow part with a temperature of 1,000-1,500 °C [15]. This makes hydrogen a promising fuel for use in the steam generators of thermal and nuclear power plants.

Problems related to investigating the following have been poorly studied to date: the process of hydrogen combustion in oxygen by using numerical methods; designing combustion chambers (CC) with an enhanced combustion efficiency, especially during transition operating conditions; reliable cooling of thermally stressed CC parts and reduced heat loss to the environment.

Issues related to the following have been poorly studied to date: the effect of turbulising insert elements at the inlet of the hydrogen-oxygen steam generator on the processes of combustion and formation of reaction products.

The paper uses numerical methods to evaluate the effect of inlet flow turbulisation, and the flow rate and method of feeding extra water to the combustion chamber on the processes of combustion of the stoichiometric hydrogen-oxygen mixture.

Materials and methods
The paper considers the process of combustion of a stoichiometric hydrogen-oxygen mixture in the three-dimensional unsteady problem statement. The research structure is shown in Fig. 1.

Experimental part
The schematic diagram of the experimental setup is shown in Fig. 2.

Figure 1. The research structural diagram

Figure 2. Schematic diagram of the experimental setup

Hydrogen and oxygen were generated using an alkali electrolyser, and the gases were cleaned of steam with a separator.

The following parameters were monitored during the experiment: the hydrogen-oxygen mixture flow rate and temperature; the waste gases composition (with a gas analyser)
and the waste gases temperature (with a chromel-alumel thermocouple in the stagnated flow), Fig. 3.

Figure 3. Experimental setup diagram

The authors [24] investigated the changes in the flame length, the lift-off height, the temperature, the flame composition and the emission indices of the species in the post-flame region for a turbulent flame of a methane-air stream without preliminary mixing. The suggested research technique enabled to evaluate changes in the flame geometry, the reduction in flame temperature and the reduction in NO\textsubscript{x} concentration at various levels of dilution of carbon dioxide in the fuel.

The combustion of the hydrogen-oxygen mixture (primary reaction) is considered with account of 15 intermediate reactions (Table 1) [16, 17, 25].

Primary reaction:

\[ H_2 + \frac{1}{2}O_2 = H_2O + 241 \]

In the paper, the turbulent flows were described with account of recommendations in [26-28], and the standard \( k-\varepsilon \) model [29-31] turbulence model was used.

The standard \( k-\varepsilon \) model equations have the form [32]:

\[
\frac{\partial}{\partial t}(\rho \cdot k) + \frac{\partial}{\partial x_i}(\rho \cdot k \cdot \bar{u}_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \\
+ G_k + G_b - \rho \cdot \varepsilon - Y_M + S_k,
\]

\[
\frac{\partial}{\partial t}(\rho \cdot \varepsilon) + \frac{\partial}{\partial x_i}(\rho \cdot \varepsilon \cdot \bar{u}_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \\
+ G_{1e} \frac{\varepsilon}{k} (G_k + C_{3e} \cdot G_b) - C_{2e} \cdot \rho \frac{\varepsilon^2}{k} + S_\varepsilon,
\]

\( k \) is the specific kinetic turbulent energy; \( \varepsilon \) is the rate of the viscous dissipation of turbulent energy; \( \rho \) is the gas density; \( \mu_t \) is the turbulent dynamic viscosity; \( \bar{u}_i \) is the averaged velocity; \( \sigma_k \) is a dimensionless empirical constant; \( G_k \) is the turbulent kinetic energy formed by mean velocity gradients; \( G_b \) is the displacement force kinetic energy; \( C_{3e} = 1 \) (for liquid layers, with the liquid velocity direction being parallel to the gravitation vector), \( C_{3e} = 0 \), \( C_{3e} = 1 \) (for liquid layers, with the liquid velocity direction being perpendicular to the gravitation vector), \( C_{2e} = 1.92 \), \( C_{1e} = 1.44 \) are constants [32, 33]; \( Y_M \) is the contribution of the variable expansion during compression turbulence to the total dissipation rate; \( S_k \) is the invariant of the strain tensor.
Table 1. Intermediate reactions with participation of $O_2$, $O$ and $OH$ in reacting mixtures ($H_2 + O_2 +$ inert gas)

<table>
<thead>
<tr>
<th>№</th>
<th>Reactions</th>
<th>$k^0_r(T), (in \text{ cm}^3/\text{mole, s})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$HO_2 + H_2 \leftrightarrow OH^* + H_2O$</td>
<td>$3.0 \cdot 10^{15} \cdot (T/298)^{-1.7} \cdot \exp(-1900/T)$</td>
</tr>
<tr>
<td>2</td>
<td>$O^* + H + M \leftrightarrow OH^* + M$</td>
<td>$7.0 \cdot 10^{15} \cdot (T/298)^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$O + H + M \leftrightarrow OH^* + M$</td>
<td>$1.0 \cdot 10^{16} \cdot (T/298)^{-1} \cdot \exp(-1200/T); \ M = OH : 2.0 \cdot 10^{15} \cdot (T/298)^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$OH^* + M \leftrightarrow OH + M$</td>
<td>$M = H_2O : 2.2 \cdot 10^{14} \cdot \exp(-276/T)$; $H_2 : 1.0 \cdot 10^{12}; \ M = O_2 : 6.0 \cdot 10^{12}; \ Ar : 1.3 \cdot 10^{11} \cdot (T/298)^{0.5}$</td>
</tr>
<tr>
<td>5</td>
<td>$OH^* + O_2 \leftrightarrow O_3 + H$</td>
<td>$4.0 \cdot 10^{13} \cdot (T/298)^{0.5}$</td>
</tr>
<tr>
<td>6</td>
<td>$OH^* + H_2O \leftrightarrow H_2O_2 + H$</td>
<td>$7.5 \cdot 10^{12} \cdot \exp(-276/T)$</td>
</tr>
<tr>
<td>7</td>
<td>$OH^* + H_2 \rightarrow H_2O + H$</td>
<td>$8.8 \cdot 10^{13} \cdot (T/298)^{0.5}$</td>
</tr>
<tr>
<td>8</td>
<td>$OH^* + O_2 \rightarrow HO_2 + O$</td>
<td>$2.0 \cdot 10^{13} \cdot (T/298)^{0.5}$</td>
</tr>
<tr>
<td>9</td>
<td>$OH^* \rightarrow OH + hv$</td>
<td>$1.4 \cdot 10^6$</td>
</tr>
<tr>
<td>10</td>
<td>$HO_2 + H \rightarrow H_2O + O^*$</td>
<td>$2.3 \cdot 10^{13} \cdot (T/298)^{0.458} \cdot \exp(-678/T)$</td>
</tr>
<tr>
<td>11</td>
<td>$O^* + H_2 \leftrightarrow OH + H$</td>
<td>$\approx 1 \cdot 10^{14} \cdot \exp(-20000/T)$</td>
</tr>
<tr>
<td>12</td>
<td>$O^* + H_2 \rightarrow H_2O$</td>
<td>$\approx 1 \cdot 10^{14}$</td>
</tr>
<tr>
<td>13</td>
<td>$O^* + M \leftrightarrow O + M$</td>
<td>$M = H_2 : 1.0 \cdot 10^{14}; \ O_2 : 2.0 \cdot 10^{11}; \ Ar : 2.0 \cdot 10^{11}$</td>
</tr>
<tr>
<td>14</td>
<td>$H + HO_2 \leftrightarrow H_2 + O_2^*$</td>
<td>$6.5 \cdot 10^{11} \cdot (T/298)^{1.671} \cdot \exp(-3162/T)$</td>
</tr>
<tr>
<td>15</td>
<td>$O_2^* + M \leftrightarrow O_2 + M$</td>
<td>$M = H_2 : 2.7 \cdot 10^6; \ O_2 : 1.0 \cdot 10^6; \ Ar : 3.0 \cdot 10^5$</td>
</tr>
</tbody>
</table>
The turbulent flows of gases during perturbation by the water spray were described using the standard $k-\varepsilon$ turbulence model, and that of water was described using the dispersed phase zero equation.

Basic model equations:

$$\frac{\partial (\alpha_k \rho_k u_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k u_k \bar{u}_k) = \Gamma_k$$

$\alpha_k$ is the volume fraction; $\Gamma_k$ describes the mass transfer between phases; $\bar{u}_k$ is the stress tensor of the ‘$k$th’ phase; $\tilde{r}_k$ is the stress tensor of the ‘$k$th’ phase due to the presence of the other phases.

The Eddy Dissipation Model (EDM) [37, 38] was used for describing the combustion process:

$$\rho S_i = A \nu_{kr}^i M_{w,r} \rho \varepsilon \left( Y_k - \sum_{p} \frac{Y_p}{B \sum_{r} \nu_{lp}^i M_{w,r}} \right)$$

where $\nu_{kr}^i$ is the reaction stoichiometric coefficient, $Y_k$ is the mass fraction of the particular reactant species (H$_2$) and $Y_p$ is the mass fraction of the product species (H$_2$O). The model constants are $A = 4.0$ and $B = 0.5$.

The description of the complex heat transfer between the gas, flame and walls in the paper accounts for radiant heat transfer by using the P1 model [29, 33, 38]. The equation of the P1 radiant heat transfer model has the form:

$$q_r = \frac{1}{3(\alpha + \sigma_s) - C \sigma_s} \cdot \nabla G,$$

where $\alpha$ is the absorption coefficient, $\sigma_s$ is the scattering coefficient, $G$ is the incident radiation,
C is the linear-anisotropic phase function coefficient. The spectral incident radiation:
\[
\nabla \left( \frac{1}{3(K_{av} - K_{vs}) - AK_{vs}} \nabla G_v \right) = K_{av} (G_v - 4E_{av}),
\]
where A is the linear anisotropy coefficient.

The boundary condition at the walls is:
\[
n \cdot q_v = -\frac{1}{3(K_{av} - K_{vs}) - AK_{vs}} \frac{\partial G_v}{\partial n^+} = \frac{\varepsilon_v}{2(2 - \varepsilon_v)} \left[ 4E_{av} - G_v \right]_v,
\]
where n is the unit vector outward normal to the wall; n+ is the distance coordinate in the same direction, representing the value at the wall.

Next, the parameters of the mathematical models were verified and adjusted to describe the process of combustion of the stoichiometric hydrogen-oxygen mixture in a laboratory-scale burner with a simplified flow part geometry.

Fig. 4 is the photograph of combustion of the stoichiometric hydrogen-oxygen mixture in the laboratory-scale burner.

The flame colour changes from yellow to red owing to the burn-off of metal particles (nozzle material – stainless steel) that occurs during hydrogen and oxygen flow. This effect was not account for in the computations.

Table 2 shows the experimental results. Fig. 5 illustrates the results of unsteady numerical simulation of the process of combustion of the hydrogen-oxygen mixture.

The maximum flame temperature reaches 3,000 °C (Fig. 5). With distance from the nozzle, the flame temperature drops from 2,400 to 800 °C. The flame geometric characteristics (Fig. 5) are in good agreement with the results of the conducted experiment (Fig. 4) and Table 2.

Table 2 shows the comparison of computational and experimental results.
Table 2. Comparison of experimental and computational results

<table>
<thead>
<tr>
<th>Results</th>
<th>Flame size, mm</th>
<th>Temperature</th>
<th>NO concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Experiment</td>
<td>4.6</td>
<td>6.5</td>
<td>10</td>
</tr>
<tr>
<td>Computation</td>
<td>4.7</td>
<td>6.1</td>
<td>11</td>
</tr>
<tr>
<td>Error percentage</td>
<td>2.17</td>
<td>6.15</td>
<td>10</td>
</tr>
</tbody>
</table>

The differences in the geometric dimensions of the flame (computation-experiment) stem from the complexity of describing and simulating combustion processes, and the accuracy of determining the flame boundaries (zones) by experimental data. As concerns the macro indicators (main flame dimensions, temperature and NO concentration) for such complex processes, the error is within admissible limits.

The results in Figs. 4-5 and Table 2 demonstrate that the use of the standard $k$-$\varepsilon$ model turbulence model and the chosen adjustments of the parameters of the mathematical models yield acceptable numerical simulation results.

Based on the conducted research, further design simulations will use the standard $k$-$\varepsilon$ turbulence model [29-31]. They will involve numerical simulation of the combustion of the stoichiometric hydrogen-oxygen mixture in the auxiliary steam generator.

The flow part length is 200 mm and the diameter of the water-cooled CC is 75 mm. A nozzles unit located 70 mm away from the CC is provided for feeding water to the steam generator.

To evaluate the influence of the discretization level and the increase of the accuracy of numerical simulation results, the paper considers three variants of the level of discretization of the computational domain. The computational cells used for numerical simulation are shown in Fig. 7 and their dimensions, in Table 3. The flow part of the steam generator is a body of rotation (Fig. 6).
Figure 7. Numerical mesh for numerical simulation

Table 3. Number of numerical meshes with a different level of discretization of the computational domain

<table>
<thead>
<tr>
<th>Variant</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of numerical mesh cells, mln.</td>
<td>0.381</td>
<td>0.515</td>
<td>1.02</td>
</tr>
</tbody>
</table>

To increase the accuracy of modelling near-wall effects during the flow of the gases and their combustion, the numerical mesh was adapted in the papers [39-41]. This paper uses numerical meshes having five layers in the near-wall layer with a minimal cell height of 0.1 mm.

The scheme for specifying boundary conditions (BC) is shown in Fig. 8, and the BC values are given in Table 4.

Table 4. Values of boundary conditions

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Boundary type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ in</td>
<td>Inlet velocity, m/s</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Temperature, °C</td>
<td>25</td>
</tr>
<tr>
<td>H₂ in</td>
<td>Inlet velocity, m/s</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Temperature, °C</td>
<td>25</td>
</tr>
<tr>
<td>H₂O in</td>
<td>Inlet velocity, m/s</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Temperature, °C</td>
<td>95</td>
</tr>
<tr>
<td>Out flow</td>
<td>Excess pressure, MPa</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Ambient temperature, °C</td>
<td>500</td>
</tr>
<tr>
<td>Wall</td>
<td>Ambient temperature, °C</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Heat transfer coefficient, W/(m²K)</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Wall roughness, µm</td>
<td>30</td>
</tr>
</tbody>
</table>

Results

The results of numerical simulation of the process of hydrogen combustion in oxygen with feed water in the steam generator flow part are shown in Figs. 9-12.

Fig. 9 shows the gas and flame temperature distributions. The maximum temperature is in the peripheral area of the combustion chamber, and it reaches 2,721 °C. With distance from the combustion chamber, the temperature drops from 2,100 to 1,368 °C.

The irregularity of temperature distribution along the combustion chamber radius (Fig. 9b) is due to the swirl of the hydrogen-oxygen mixture flow.
The obtained temperature distribution in the combustion chamber volume is attributed to the action of water on the combustion process of the hydrogen-oxygen mixture. During interaction of the flame with the extra water, due to the contrast in density, the water drives the flame towards the walls, with the flame and water contact area having the shape of a deformed paraboloid (Fig. 10).

A feature of the suggested steam generator design is the presence of a swirler at the inlet and the realisation of the combustion process within the limits of the forced water cooling of the combustion chamber (further, this water is fed to the steam generator through nozzles arranged perpendicularly to the generator’s axis). This excludes flame extraction along the flow part axis and reduces irrecoverable heat losses through the walls to the environment.

In the wall layer, the gas and flame temperatures drop from 2,200 K to 1,120 K. With such a combustion mode, the maximum wall temperature does not exceed 850 °C. This is not critical for the combustion chamber material – refractory steel.

Such a temperature distribution during combustion of the hydrogen-oxygen mixture is due to the presence of turbulent flows and the action of the feed water on the burning process (Fig. 11).
The results (Fig. 11) show that the combustion process is stabilised in 5 seconds after its starting, with account of the small steam generator dimensions.

The flow velocity distribution is shown in Fig. 12. The maximum velocity is in the zone of the water feed nozzles and it reaches 350 m/s. With distance from the water feed nozzles, the flow velocity drops from 220 to 105 m/s.

Such an irregular distribution of the flow velocity is the result of complex heat-and-mass transfer processes in the steam generator combustion chamber, and of the arrangement of the nozzles for feeding extra water.
The extra water fed to the steam generator perpendicularly to its axis creates a curtain, with the flow being decelerated to reduce the velocity in the flow part central zone to 7.2 m/s (Fig. 12 a).

The accuracy of the problem formulation and the solution was evaluated with account of the balance of masses at the steam generator inlet and outlet (Table 5).

**Table 5.** Mass balance at the gas burner inlet and outlet

<table>
<thead>
<tr>
<th>Inlet flow</th>
<th>Out flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2 kg/s</td>
<td>0.005</td>
</tr>
<tr>
<td>H2 kg/s</td>
<td>0.000687</td>
</tr>
<tr>
<td>H2O kg/s</td>
<td>0.0263</td>
</tr>
<tr>
<td>All fluid</td>
<td>0.0317</td>
</tr>
</tbody>
</table>

The results in Table 5 show that it was possible to achieve good agreement of flow rates at the inlet and outlet of the steam generator. This is indicative of an accurate problem formulation. The mass imbalance between the inlet and outlet is within 0.63%.

**Discussion**

The influence of the discretization level on the numerical simulation results is shown in Table 6.

**Table 6.** The influence of the level of discretization on numerical simulation results

<table>
<thead>
<tr>
<th>Number of computational cells, mln.</th>
<th>Maximum temperature, °C</th>
<th>Water steam temperature at steam generator outlet, °C</th>
<th>Mass fraction of hydrogen at steam generator outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.381</td>
<td>2,755</td>
<td>1,391</td>
<td>0.00152</td>
</tr>
<tr>
<td>0.515</td>
<td>2,728</td>
<td>1,375</td>
<td>0.00157</td>
</tr>
<tr>
<td>1.02</td>
<td>2,721</td>
<td>1,368</td>
<td>0.00168</td>
</tr>
</tbody>
</table>

The results in Table 6 demonstrate that the further increase of the number of computational cells (over 1 million) is impractical and leads to a growth of problem dimensionality without a substantial increase in the accuracy of numerical simulation results. The maximum temperature difference with a 3-fold increase of the discretization level is 1.2 %.

The estimates of the effect of the feed water flow rate on the combustion process in the steam generator are shown in Table 7 and Fig. 13.

**Table 7.** The effect of the feed water flow rate on the combustion process in the steam generator

<table>
<thead>
<tr>
<th>№</th>
<th>Steam generator feed water mass flow</th>
<th>Steam mass flow</th>
<th>Steam temperature at steam generator outlet</th>
<th>Mass fraction of hydrogen at steam generator outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G_{H2O} kg/s</td>
<td>G_{st} kg/s</td>
<td>T_{st} °C</td>
<td>H_{2MF}</td>
</tr>
<tr>
<td>1</td>
<td>0.0061</td>
<td>0.012</td>
<td>2,650</td>
<td>0.00121</td>
</tr>
<tr>
<td>2</td>
<td>0.0094</td>
<td>0.0157</td>
<td>2,230</td>
<td>0.00151</td>
</tr>
<tr>
<td>3</td>
<td>0.0263</td>
<td>0.0317</td>
<td>1,368</td>
<td>0.00168</td>
</tr>
<tr>
<td>4</td>
<td>0.168</td>
<td>0.174</td>
<td>576</td>
<td>0.00250</td>
</tr>
<tr>
<td>5</td>
<td>0.529</td>
<td>0.530</td>
<td>495</td>
<td>0.00274</td>
</tr>
</tbody>
</table>

The results in Table 7 and Fig. 13 show that an increase in the mass flow rate of the steam...
generator feed water to over 0.0317 kg/s leads to a reduced fuel efficiency and a sharp steam temperature drop. This is explained by the increase in the heat capacity of the steam-and-gas mixture (with an increased steam content) and the expenditure of much energy on water evaporation and heating, with an adverse effect on combustion efficiency.

This also has an adverse effect on the performance of the system for feeding extra steam to the steam turbine intermediate pressure stage.

The paper considers other steam generator design variants as an alternative to the suggested construction (Fig. 14).

Numerical simulation results were obtained using identical mathematical models and source data (Figs. 15-20).

Fig. 15 illustrates the flame temperature distribution along the steam generator axis.

The maximum temperature is in the central area of the steam generator and it reaches 2,739 K. Close to the combustion chamber walls, the temperature varies from 2,000 to 1,500 K.

Fig. 16 illustrates the flow velocity distribution along the steam generator axis.

Figure 14. Steam generator design variants: 1 – baseline; 2 – tangential water feed; 3 – without a swirler

Figure 15. Temperature distribution in the steam generator flow part during combustion of hydrogen in oxygen (design variant 2)
The maximum velocity reaches 285 m/s in the central part of the steam generator (Fig. 16). Due to the involved design and the proceeding processes, the flow velocity distribution is irregular.

Distribution of the steam mass share in the process of combustion of the hydrogen-oxygen mixture is shown in Fig. 17.

Flame extension and the formation of an isosurface on the flame-steam interface along the flow part axis is the result of emergence of a low-density steam-gas mixture in the central zone through which the flame spreads.

Such a combustion mode is accompanied by hydrogen afterburning beyond the cooled part of the combustion chamber and declining fuel combustion efficiency.

Figures 18-20 show the isosurfaces of the mass share of the steam $MF_{H_2O} = 0.99$ and the distribution of local temperatures for three steam generator design variants.
For design variant 2 (Fig. 19), the isosurface form is a deformed cylinder facing the steam generator outlet orifice. Such a direction and isosurface form are the result of tangential feed of extra water and the occurrence of a steam-and-gas interspace in the centre of the steam generator flow part, through which the flame spreads.

The maximum temperature reaches 2,283 K in the isosurface base zone. The temperature varies from 2,000 to 477 K along the isosurface length.

Fig. 20 shows the isosurface of the steam mass share for design variant 3.

Figure 20. Isosurface of the steam mass share \( MF_{H2O} = 0.99 \) and the distribution of local temperatures (design variant 3): a – side view; b – frontal view

The form and orientation of the isosurface resembles that for design variant 1, though with smaller deformation of the base. This is due to absence of a swirler. The maximum temperature is at the isosurface base and reaches 2,362 K (Fig. 20). In the apex zone, the temperature varies from 1,300 to 1,800 K.

Tables 8 and 9 show the results of numerical simulation of the effect of steam generator design parameters on the process of the combustion of the hydrogen-oxygen mixture.

Table 8. Effect of the steam generator design on the parameters of the flame-steam interface

<table>
<thead>
<tr>
<th>Design variant, No.</th>
<th>( S_c ), m(^2)/**</th>
<th>( T^{*<strong>} ), K/</strong></th>
<th>Mass share of ( H_2 ) on the flame-steam interface/**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0099/-</td>
<td>2,071/-</td>
<td>0.00385/-</td>
</tr>
<tr>
<td>2</td>
<td>0.0115/16</td>
<td>1,056/49</td>
<td>0.00403/4.9</td>
</tr>
<tr>
<td>3</td>
<td>0.0099/0</td>
<td>1,896/8.5</td>
<td>0.00438/14</td>
</tr>
</tbody>
</table>

* – isosurface area on the flame-steam interface; ** – percentage change (%); *** – averaged isosurface temperature on the flame-steam interface.

Table 8 shows that the best conditions for realising an effective hydrogen-oxygen mixture combustion process belong to design variant 1. With a minimal flame-steam area of contact, it has the highest temperature on the interface and the lowest mass share of unburnt hydrogen.

Table 9. Effect of the steam generator design on the combustion mode (the mode with the steam flow rate \( G_{st} = 0.0317 \text{ kg/s} \))

<table>
<thead>
<tr>
<th>Design variant, No.</th>
<th>Maximum temperature, ( \circ C/* )</th>
<th>Gas temperature in the interface layer, K</th>
<th>Water steam temperature at the steam generator outlet, ( \circ C/* )</th>
<th>Share of unburnt fuel (%)/**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,721/-</td>
<td>1,120/-</td>
<td>1,368/-</td>
<td>7.7/-</td>
</tr>
<tr>
<td>2</td>
<td>2,739/</td>
<td>780/30</td>
<td>1,178/14</td>
<td>10/30</td>
</tr>
<tr>
<td>3</td>
<td>2,528/</td>
<td>1,00/9</td>
<td>1,379/0.8</td>
<td>8.7/13</td>
</tr>
</tbody>
</table>

* – percentage change (%).

Table 9 shows that the most effective steam generator design variant is No. 1. Its maximum flame temperature reaches 2,721 K and in the interface layer, it is within 1,120 K. The unburnt fuel share is within 7.7%, and this in agreement with the results of other authors [42].
The biggest unburnt fuel share (10%) was found in design variant 2. This is the result of flame extension along the flow part length and fuel afterburning under unfavourable conditions.

**Conclusions**

The research yielded the following results:

- the standard $k$-$\varepsilon$ turbulence model yields informative results during the simulation of the process of combustion of the stoichiometric hydrogen-oxygen mixture with a high rate and pressures in both the wall areas and the central zone of the steam generator;
- during combustion of the stoichiometric hydrogen-oxygen mixture in the steam generator with water feed the flame temperature reaches 2,721 °C in the peripheral area of the combustion chamber. This is due to the turbulence of the fuel and oxidizer flow and the effect of feeding extra water.
- increasing the mass flow of the steam generator feed water to over 0.0317 kg/s reduces the steam temperature lower than the admissible limits (less than 1,300 K). This results in an increasing share of unburnt fuel at the steam generator outlet.
- the research has shown that design variant 1 with inlet flow turbulisation (with a swirler installed) and extra water feed in a direction perpendicular to the steam generator axis combines high steam generation capacity (0.0412 kg/s for a 1-litre steam generator) with an acceptable steam temperature (1,368 K) and a minimal share of unburnt fuel (7.7%), with the temperature of the water-cooled combustion chamber walls not exceeding 850 °C;
- the research results can be used to predict the performance indices of hydrogen-oxygen steam generators and improve them.
- as a fuel, hydrogen has a significant potential in both the power industry and transport. The challenging issues are generation systems (with low energy consumption levels), and storage and usage (direct firing and oxidation in fuel cells).

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**References**


