Top-Combustion Solid Fuel-Fired Boilers: Peculiarities of Combustion as Observed in-kind in the North

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Abstract: In the climate of the Republic of Sakha (Yakutia), it is important to have efficient and reliable heat sources to survive. This is why efficient standalone heat generators are becoming ever more popular. As of lately, Yakutia’s residents tend to prefer detached housing with individual heating. However, practical experience has shown that neither domestically made nor imported heat generators are suitable for the Republic’s cold climate. This statement is reinforced by their poor heating performance that does not match the manufacturers’ claims. Such performance is mainly due to failing flue-gas stacks, a phenomenon associated with the air-fuel equivalence ratio.

1. Introduction

Yakutia’s public utilities comprise heat generation facilities, hear-transfer fluid transport, and infrastructural facilities. In nearly every city and municipality of the Republic, district heating systems are collapsing and cannot function properly. On average, 56.9% of such systems and their components are worn out [1, 2].

Public utilities are facing many problems, most notably:
1. Poor public utility services due to the wear and tear of the infrastructures they use;
2. Excessive wear and tear of the public utility facilities themselves;
3. Prohibitive costs of fuel and energy.

Annual temperature range varies from 50°C to 127°C; the coldest five days have outdoor air temperatures from -50 to -65 degrees, cf. -25°C to -41°C in the rest of Russia—the difference exceeds 20 degrees. Annual temperature range is outstandingly broad in Yakutia. The climate of Yakutsk has some specific features that are most striking when compared against the climate of Central Russian cities, see Figure 1.
The heating season is long, permafrost is present, the infrastructure is underwhelming, and human settlements (mostly quite underpopulated) are distanced substantially from each other. All of this makes construction and living in the north a challenging undertaking [3, 4, 5]. In the climate of the Republic of Sakha (Yakutia), it is important to have efficient and reliable heat sources to survive.

2. Methods

Individual heating systems are faster and cheaper to construct, sustain less heat losses, are not affected by heat leakage associated with transporting a heat-transfer fluid over an external network, do not incur costs to maintain and operate heating lines, can be controlled on the site, etc. These are important advantages [6]. The specific features and general properties of individual heating systems have been described by G.M. Klimov, V.I. Sologayev, O.K. Mazurova, N.V. Kuznetsov, A.N. Butenko et al. [7, 8]. Since the 2010s, Yakutia has been adopting top-combustion solid fuel-fired boilers. As of today, the Republic has over 1000 such units in operation. They are mainly brown coal or firewood-fired. A top combustion heating boiler is a cylindrical enclosure that contains a combustion chamber, a fire grate, a heat-transfer fluid tank, and an air feeder. The key feature is that the combustion process uses little oxygen, thus being able to extract heat from the fuel for a longer time and producing less solid waste. This is a candle-like combustion process: while the top layers are burning, the bottom layers are waiting for their turn and release no heat [9, 10]. To function properly, such a heat generator will need air fed continuously to the combustion chamber, hot gases moving at a constant desired rate, and the combustion products removed by draft [11, 12].

The natural available pressure of the flue-gas stack $H_c$ can be found by the formula:

$$H_c = h \cdot g (\rho_s - \rho_f)$$

where $h$ is the height of the stack, m; $g$ is the free-fall acceleration, m/s$^2$; $\rho_s$ is the air density, kg/m$^3$; $\rho_f$ is the flue gas density, kg/m$^3$.

This equation makes it clear that the draft induced by the flue-gas stack will be stronger in higher stacks at higher temperatures of the exhaust gas. In-kind observations produced the curve of the available gravity pressure as a function of outdoor sir temperature for different flue-gas stack heights in solid-fuel boilers, see Figure 2. The compared systems were running under identical conditions, assuming equally powered heat generators, identical flue-gas stack diameters and fuels.
Figure 2. Available gravity pressure as a function of the outdoor temperatures for (I) 4.5 m; (II) 6 m; (III) 8 m; (IV) 10 m high flue-gas stacks.

The calculations made for the operating conditions typical of Yakutia showed that a greater draft in the stack would increase the gas velocity, inflating fuel consumption. Practice shows that solid fuel-fired heat generators, whether made in Russia or imported, are not suitable for the cold climate of the country’s North and fail to meet their own specifications in terms of combustion duration, efficiency, and heat output. A group of the Engineering Institute, North-Eastern Federal University, carried out in-kind research to make heat generators more efficient. Research was carried out in winter in 2018-2020 when the boilers were effectively in operation.

3. Results
Top-combustion solid-fuel boilers operated at extremely low temperatures in Yakutsk were studied instrumentally in kind. Studies were carried out during the cold season 2019-2020. KGA-8, a portable flue-gas analyzer, was used to quantify the efficiency of top-combustion boilers by means of the inverse heat balance method. Outdoor air temperature was measured by a Testo 435-4 unit and a SATG-90 thermographic camera.

1. Experimental data helped identify loss of heat carried away by the exhaust gas as a function of the air-fuel equivalence ratio and exhaust gas temperature, see Figure 3. Loss of heat to exhaust gases varied from 13% to 45%.
Figure 3. Curve of heat loss as a function of air-fuel equivalence ratio and exhaust gas temperature.

As can be seen in the figure, hotter exhaust gases make the air-fuel equivalence ratio affect the heat loss rate to a greater extent.

2. The research team also identified the phase transition point in the second range (-43°C), at which the boiler would lose its operational properties, see Figure 4. At this point, smoldering shifts to the intensive combustion of the upper coal layers, which increases fuel consumption and lowers the efficiency. Therefore, at peak temperatures the volume of exhaust gas leaving the system through the flue-gas stack will rise, compromising the boiler performance and increasing the air-fuel equivalence ratio.

Figure 4. Natural draft in the flue-gas stack of an extended-combustion boiler as a function of the outdoor air temperature.
3. Measurements also showed that higher O\textsubscript{2} concentrations in the flue gas were associated with a lower heating performance due to a higher air-fuel equivalence ratio resulting in hotter flue gases. The results are shown in Figure 5.

![Figure 5](image_url)

**Figure 5.** Boiler efficiency as a function of O\textsubscript{2} percentage in the combustion products.

4. It was also found out that at or below -35ºC, the flue-gas stack would partially freeze. In turn, this disrupted the heat generator since ice and snow would narrow the aperture of the stack.

4. **Conclusions**

1. Analysis of how climate affected the functioning of solid fuel-fired long-combustion boilers in Yakutia has found out that at -43ºC, heterogeneous combustion transitions into normal combustion. Boiler efficiency depends on the flue-gas stack draft. Among other things, it is the outdoor air gauge pressure and the wind-induced pressure that contribute to a greater draft in the boiler and in the flue-gas stack. The resulting pressure force depends directly on the flue-gas stack height as well as on the outdoor air temperature [13].

2. Using a draft stabilizer helps compensate the excess draft. It prevents boiler detonation by automatically reducing the air feed. This means there needs to be designed an excess draft compensator that would be activated at extremely low outdoor air temperatures, being connected to a servo drive [14-15].

3. There are multiple approaches to avoiding the effects of condensation. Those include using corrosion-resistant materials, pre-drying the fuel to reduce moisture, and enlarging the heat insulation layer in the stack.

4. Thermal insulation and architecture of buildings do affect boiler performance and the combustion rates [16]. In the Far North, a lot of heat leaks through the envelope of a wooden house, which affects the performance and efficiency of boilers and heating systems.

5. **References**

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