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Numerical Investigation of Intensity of Rising Flow of Hot Gases †

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Abstract: The motion of the burning gases that constitute the flame during fires is particularly intriguing from two perspectives: its impact on the stability of building structures and the process of extinguishing the fire, as well as the prevention of its further spread. This study investigates the existing zones within the flame during fires and their distinctive features. The upward movement of burning gases closely resembles that of a convective jet but occurs at significantly higher temperatures. The temperature and velocity distribution along the flame axis were investigated depending on the power of the fire. The changes in the density and velocity head along the height of the flame are presented graphically. These results can be very helpful for multi-store building with the aim to prevent floor heating due to the higher temperature of the attic of the down enclosure and to take measure for its cooling.

Keywords: fire; power of fire; buildings

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1. Introduction

In last few years, there has been a notable rise in the frequency of fire incidents, posing a considerable threat to human lives and resulting in substantial economic and ecological damage [1]. These alarming fire incidents have posed substantial challenges to the fundamental aspects of the performances of the buildings. Among various contributing factors, uncontrolled fires stand out as a major cause of building collapses, associated damages, potential injuries, and losses. Moreover, fire incidents have a significant impact on the quality of the environment.

In the aftermath of a fire, individuals often suffer from trauma due to the loss of their belongings. Among these losses, the destruction of a building is particularly distressing for property owners [2]. According to the World Fire Statistics Report 2018 No. 23, which documented fire incidents from 1993 to 2016, there were up to 4.5 million fires reported, resulting in nearly 62,000 fire-related deaths across 57 countries (International Association of Fire and Rescue Services 2018). Consequently, failing to address the underlying causes of building fire incidents can result in the inadequate performance of existing fire safety systems within buildings [3].

The progression of a fire within a confined space presents a significant risk to occupants. Engineers are consistently working to enhance the safety of individuals in buildings [4,5].

This underscores the importance of investigating the factors that contribute to construction fire incidents, which has thus far received limited research attention. Therefore, the main aim of this paper is to provide a detailed examination of the main parameters that influence building fire incidents [6,7].

2. Mathematical Model

Unlike flow streams, the distribution of burning gases upwards in natural fires is created at the expense of the lifting force. In many respects, the current resembles that of

a convective jet but differs too much in its kinetics. The flame in natural fires, according to [8], can be presented as three distinctly different zones:

1. The zone of the "steady flame". This region, located immediately below the burning surface, is where a stable flame is sustained, and the flow of burning gases experiences acceleration. It can also be referred to as the "flame zone."
2. An area of oscillating, pulsating combustion, where there is an almost constant velocity of the gas-pulsating zone.
3. A torch formed by the ascending non-isothermal current, which has all the properties of a non-isothermal jet with positive lift. In this zone, the temperature velocity decreases with height.

These three zones are interdependent and together constitute the overall flame of the fire. Nevertheless, in terms of fire extinguishing equipment and tactics, the last one, characterized by the torch created by the upward flow of burning gases, holds the utmost significance. This is primarily because several of its properties have direct implications for various aspects of fire engineering, including fire detection, smoke dispersion, and, last but not least, fire extinguishing.

The velocity, temperature of the flame, and dynamic head according to [6] are

$$u_m = kQ^{\frac{1}{5}}\left(\frac{z}{Q^{\frac{2}{5}}}\right)^{\eta}; \quad (1)$$

$$\Delta T_m = \frac{T_0}{2g}\left(\frac{k}{C}\right)^2\left(\frac{z}{Q^{\frac{2}{5}}}\right)^{2\eta-1}; \quad (2)$$

$$p_{dh} = \frac{\rho u_m^2}{2}, \quad (3)$$

where u_m—velocity of the fire, m/s; Q—power of the fire, kW; z—height of the enclosure, m; T_m—temperature of the fire, K; p_{hd}—head of the fire, Pa.

The value of parameters k, η and C are given at Table 1.

Table 1. The main parameters in different zones.

Zones	Parameters		
	k	η	C
steady flame	6.8	0.5	0.9
pulsating	1.9	0	0.9
torch	1.1	−0.33	0.9

Derived from the analysis of the initial zone, it can be inferred that $u_0 = kz^{\frac{1}{2}}$, and it can be deduced that the average velocity in the immediate proximity of the fire does not depend on its magnitude and intensity.

An increase is noticed until reaching the maximum velocity in the intermittent (pulsating) flame zone. In this zone, the average flame velocity is kept constant. According to Equation (1), it follows that the maximum value of the velocity will be proportional to the power of the fire and then $u \approx Q^{\frac{1}{5}}$.

The interaction between the dispersed extinguishing liquid and the fire flame raises a crucial question in fire extinguishing. In the case of enormous fires, which are large sources of combustion, the downward momentum of the dispersed liquid jet must prove sufficient to overcome the updraft of the burning gases. Otherwise, the water drop will be carried away by the updraft and will fail to sweep into the hot material.

3. Numerical Modelling

The influence of the fire power on the parameters of the ascending flame can be illustrated on the basis of dependences (1) and (2).

The calculations considered the boundaries of each flame area (zone). The primary finding is that as the intensity of the fire grows, the length of the respective zones also rises. The flame-resistant region lengthens from 0.22 to 0.666 as the fire power increases from 10 kW to 200 kW. The pulsating flame zone expands its length from 0.55 to 1.7 when changing in the same limits.

Figure 1 illustrates the variation in the velocity in a stable flame with variations depending on both height z [m] and the power of the fire Q [kW].

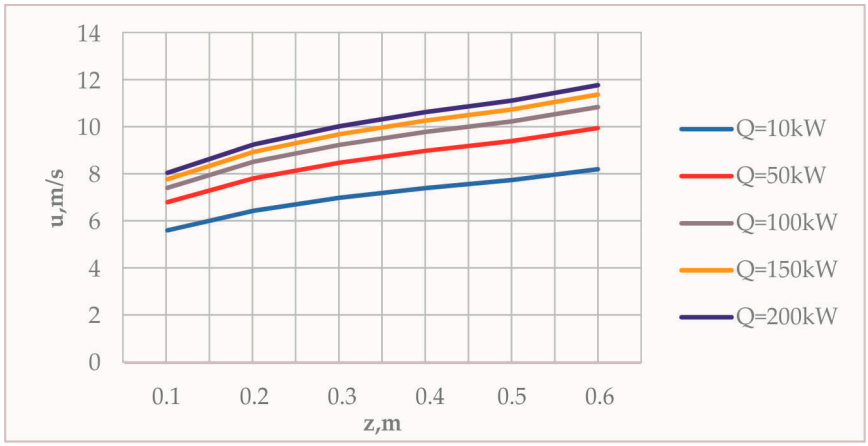

Figure 1. Distribution of the velocity for stable flame.

A characteristic feature is the acceleration of the current along z. This is analogous to the known initial zone of a convective jet, which can be explained by the strong horizontal suction of air from the environment and its rotation in a vertical direction. Increasing the firepower results in an increase in velocity, which is to be expected.

Figure 2 shows this increase depending on z and Q. This is notably more evident than the speed increase resulting from the fire's power. The temperature within this flame area remains constant.

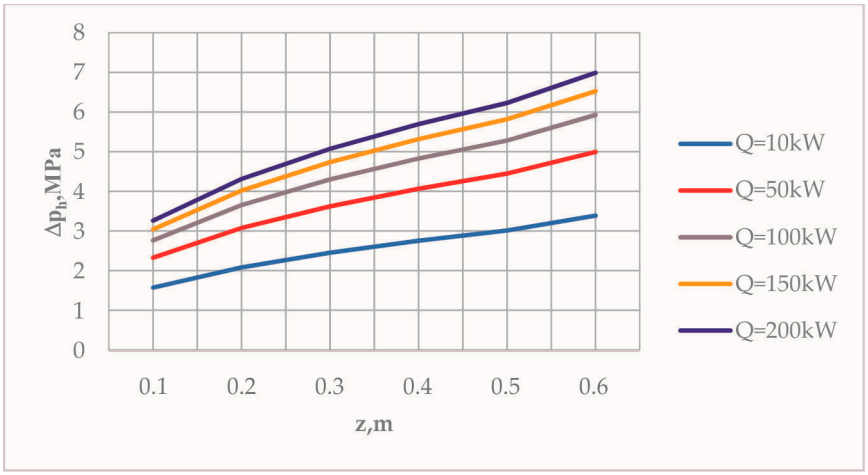

Figure 2. Distribution of the head for stable flame.

Within the region of the pulsating torch, the velocity does not change at the given distance z (as shown in Figure 3) and is solely contingent on the power of the fire. The maximum temperature difference ΔT drops, and this is the fastest at the smallest fire power values (Figure 4).

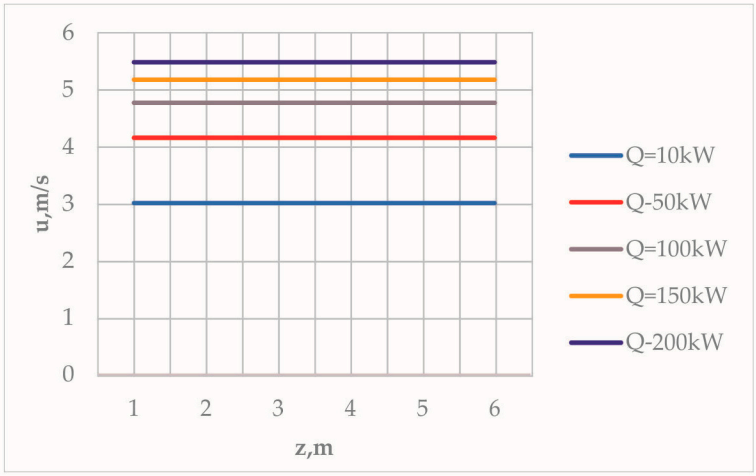

Figure 3. Distribution of the velocity for torch.

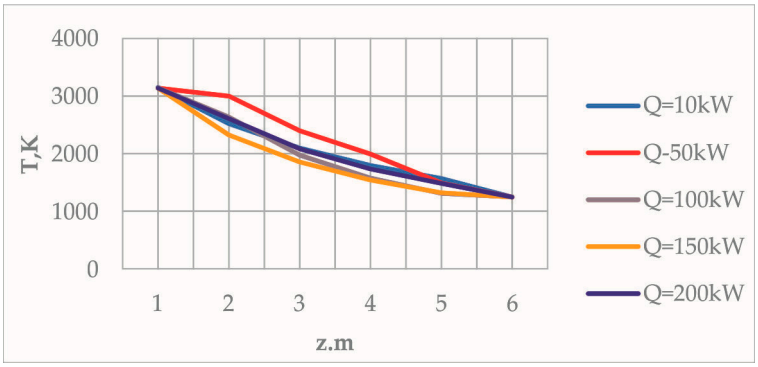

Figure 4. Distribution of the temperature for torch.

The flame density increases proportionally to the temperature $\left(\rho = \frac{p}{RT}\right)$. This results in a rise in the dynamic flame pressure, as depicted in Figure 5.

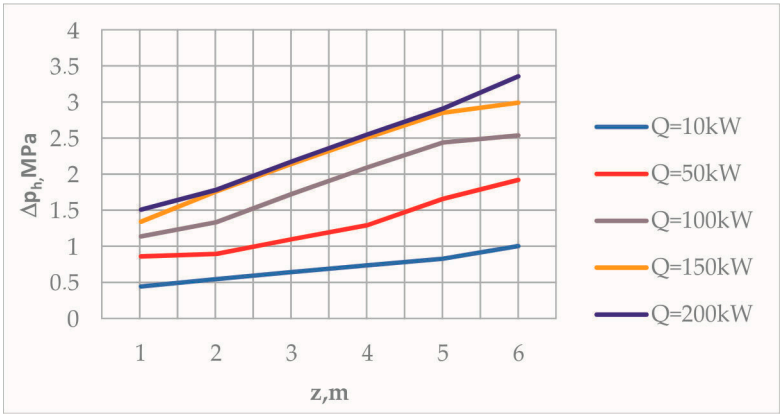

Figure 5. Distribution of the head for torch.

From the figures, it is clearly seen that with an increase in the power of the fire with a stable flame, the velocity of the fire increases, and so does its head, since it is dependent on the velocity. The velocity remains constant, which means that there is no change in pressure. Temperatures in both considered cases decrease with height but increase with increasing fire power.

In Figures 6–8, the outcomes of the velocity, temperature, and head at different heights of the enclosure are given. This height is for offices, buildings, and industrial halls [9,10].

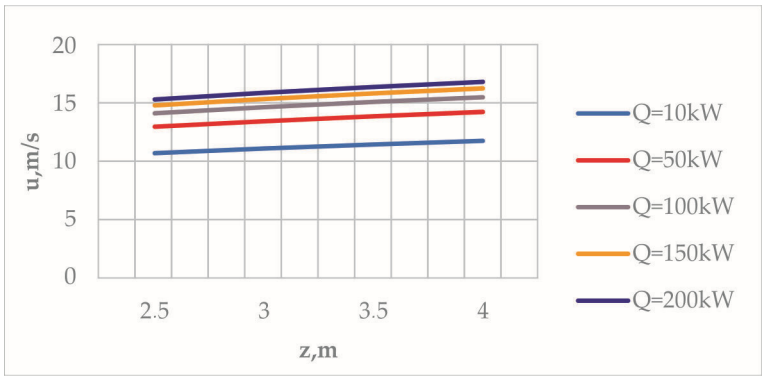

Figure 6. Distribution of velocity at different heights of the building.

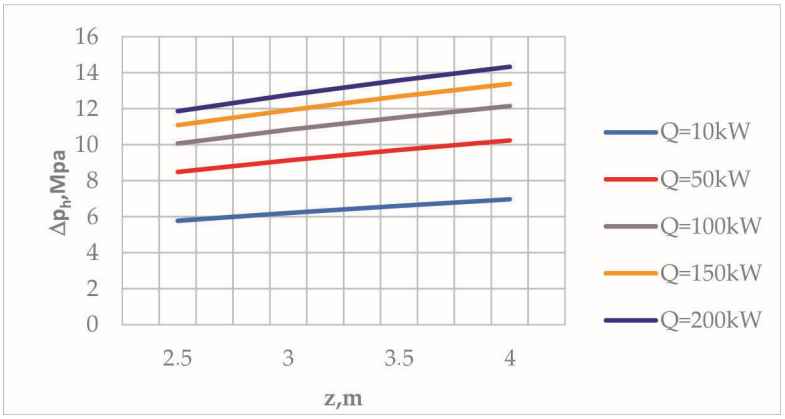

Figure 7. Distribution of head at different heights of the building.

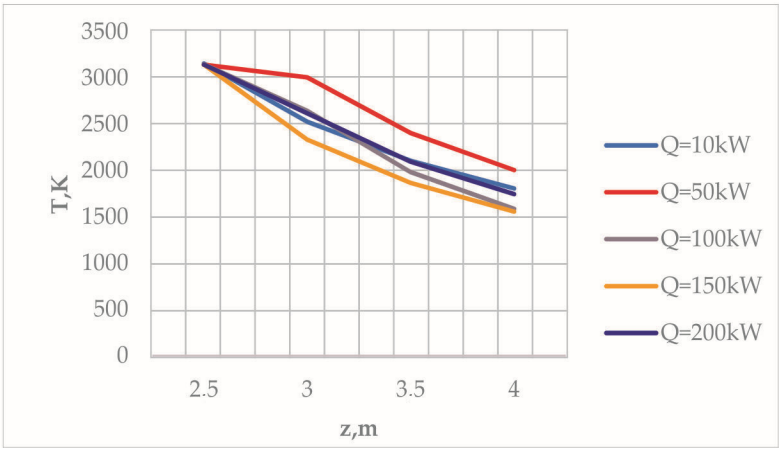

Figure 8. Distribution of temperature at different heights of the building.

The same regularity is observed from the figures shown above, namely, that as the power of the fire increases, a distinct increase in speed, pressure, and temperature is seen. And, in this case, a decrease in temperature along the height of the building is observed.

These results shown can serve as a way for fire departments to deal with building fires.

4. Conclusions

The paper is deals with a very important topic, namely the occurrence of fires in buildings. Dependencies are given by which the main parameters of the updraft can be determined. These results can also be used by the services to deal with fires more quickly. An extremely important question of firefighting arises here—the interaction of the dispersed

extinguishing liquid with the fire flame. In the case of enormous fires, which are a powerful source of combustion, the downward momentum of the dispersed liquid stream has to be enough to overcome the updraft of the burning gases. Otherwise, the water drop will be carried away by the updraft, preventing it from reaching the hot material.

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