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SOME APPROACH TO UPPER LAYER COOLING PROCESS WITH SPRAY STREAM GENERATED BY WATER NOZZLE USING COMPUTER SIMULATION METHOD

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Research article

Abstract: Computer model of upper layer cooling applying spray streams generated by water nozzle was presented in the paper. Assumptions, mathematical model and input data were given. Simulation process for assumed fire scenario and different droplet diameters was described. Results of the simulation and their analysis were presented. General conclusions and final remarks were included at the end of this work.

Keywords: Computer modelling, extinguishing system, cooling of upper layer, water nozzle, spray stream.

Nomenclature

H_0 height of a nozzle-tip position above the floor, [m]

L_p compartment length, [m]

W_p compartment width, [m]

H_p compartment height, [m]

x_p position Ox of a nozzle in a compartment system of coordinates, [m]

y_p position Oy of a nozzle in a compartment system of coordinates, [m]

δ_0 mean diameter of droplets in a spray, [mm]

d diameter of a nozzle-tip, [mm]

β inclination angle of a nozzle, [deg]

ψ solid angle of a spray, [deg]

$\overset{*}{Q}_g$ mean heat flux received from upper layer by water spray, [MW]

$\dot{V}_{pr}$ nozzle output, [dm^3/min]

w_0 mean output velocity of water droplets, [m/s]

w_{xg} horizontal coordinate of droplet velocity in a spray, [m/s]

w_{yg} vertical coordinate of droplet velocity in a spray, [m/s]

w_{sg} mean velocity of water droplets in a spray stream reaching upper layer (smoke), [m/s]

K_g extinguishing effectiveness coefficient

K_p evaporation coefficient

τ time of fire, [s]

v_0 kinematic viscosity of ambient air, [m^2/s]

v kinematic viscosity of gases in upper layer, [m^2/s]

λ_0 conductivity coefficient of ambient air, [W/(mK)]

λ mean conductivity coefficient of gases in upper layer, [W/(mK)]

D_{ew} thermal diffusivity between water and air, [m^2/s]

T_k temperature of water droplet, [K]

T_w temperature of boiling water, [K]

T_g mean temperature of upper (hot) layer, [K]

g gravitational acceleration, [m/s^2]

C Sherwood constant equal to 112

Re Reynolds number, [-]

Nu Nusselt number, [-]

Sh Sherwood number, [-]

Sc Schmidt number assumed to be 0,6, [-]

Pr Prandtl numer assumed to be 0,71, [-]

ρ_k water density, [kg/m^3]

ρ_0 gases density, [kg/m^3]

c_p izobaric specific heat of water droplet in upper layer, [J/(kgK)]

h_v heat of evaporation, [J/kg]

M_w gram-molecular of water, [kg/mol]

M_a gram-molecular of air, [kg/mol]

n_k numer of droplets vapouring totally in upper layer

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$\frac{dm_k}{dt}$ mean mass rate of vapouring of a single droplet in upper layer, [kg/s]

R universal gas constant, [8314 J/(mol K)]

Introduction

Combustion is a very complex physico-chemical process of interaction of flammable material (fuel) and air (oxidizer) characterized by release of heat and light as well as gases and smoke (Bielecki, 1996). It requires the delivery of three elements: flammable material, oxidizer and the right amount of energy, which form a triangle of combustion. When all the conditions are satisfied-fuel, heat and oxygen, the reaction is burning properly. If any of the items will be separated from the rest, or omitted, the process will be terminated. A factor involved in the combustion process is also branched chain reactions that lead to its continuity (Bielecki, 1996). These chemical reactions are as important as the other three factors (quadrangle of combustion). Extinguishing is used to stop the combustion process. It occurs by cutting or removal of one of the items needed to create and sustain this reaction. The basic means of extinguishing fires are:

a) cooling of combustion zone and flammable material (to reduce the speed of decomposition and evaporation),
b) cooling of upper layer (hot gases zone),
c) change in the composition of the reaction environment (e.g. leading to increased heat capacity),
d) disconnection of the chemical reactions,
e) limiting access to fuel,
f) restricting access of oxygen,
g) air combustion zone separation,
h) separation of flame from flammable material surface,
i) reduction of oxygen concentration in the combustion zone,
j) flammable vapour reduction by diluting inert gas,
k) changing chemical reactions by increasing speed of recombination in the presence of free radicals in the flame by active agent (combustion inhibitor) or uptake of free radicals.

Water is the most commonly used extinguishing agent, through its universality, low prices, and fire-fighting properties. In order to optimize its operation, you need to understand its characteristics and factors affecting the effectiveness of the fighting. The hydrogen peroxide in the form of a colorless liquid in layers with a thickness of more than 2 m takes the blue colour. It has no taste or smell.There is also no harmful effects on the human organism. In nature does not exist in pure form and contains a number of dissolved compounds (mainly salt). The characteristic properties of water are:

a) *small compression* (allows you to provide it under pressure from high intensity up to several m^3/min);
b) *conducting electricity*
The water due to the salt content is a good conductor to electric current. However, the application of the distributed water currents on electrical equipment under voltage reduces the electrical conductivity nearly to zero;
c) *freezing temperature*
Supplying of water is possible even at temperatures below 0 °C. However, this is only possible while maintaining a continuous flow through the hose lines. Stopping the flow can cause rapid freezing up water in the hose;
d) *boiling temperature*
Boiling water is a phenomenon that can create dangerous situations for firefighters. An example of this might be durimg extinguishing of the fats. At the time of contact of the water with a burning fat comes to rapid evaporation thereof, and to remove the air part of the fat, what causes the spread of fire and the possibility the rescuer burns;
e) *reactions with certain elements and chemical compounds*
The water reacts very strongly with some elements and chemicals compounds. The rapid process of these reactions, as well as their products poses is a high risk for firefighters. Examples of such elements can be: sodium and potassium. In turn an example of connection to respond rapidly with water is calcium carbide (Suslavicius, 2011);
f) *a large thermal capacity*
Heat capacity of water is 4.19 kJ/(kg K). However, the use of all heat capacity of water is not possible due to the technical capabilities of the supplying of water. During the supplying of it by standard nozzles this value does not exceed 1.4 kJ/(kg K). This means that about 2/3 of the water supplied to the fire has a small influence on the total effect of the extinguishing process;
g) *a large number of emerging water vapour*
After evaporation of one liter of water is approximately 1650 dm^3 vapour (Gil and Placek, 2003). It has a significant impact on the fire-extinguishing effect of water due to the ability to inerting of atmosphere.

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The main action of the water fire-extinguishing is receiving heat from burning material and the environment. Water supplied directly to combustible material evaporates, which gets a large amount of energy from the hot material. Drop the temperature of the burning of the body reduces the speed of the combustion reaction. When the intensity of the treatment of water on the burning material will be sufficient, it will be cooled enough so that combustion reaction will be stopped. Cooling is not the only mechanism of extinguishing water. Evaporating water creates water vapour that fills the room. If the concentration of water vapour in the room would be 20 - 25 %, it is impossible further to continue the process of combustion. This concentration is called the inerting concentration (Bielecki, 1996).

Physico-chemical properties of the water decide about its extinguishing effectiveness. However, it depends largely on how it is supplied to the combustion zone. When extinguishing a fire is important not only to put out it, but to make this using the least amount of water. Stop the combustion reaction is possible if the water stream receives the heat faster than it is produced by burning materials. The sooner this happens, the need is less amount of water. In the case of spray stream speed evaporation rate, which is approximately proportional to the total surface evaporation, increases with the fragmentation of water stream. On the other hand, an increase in fragmentation of water flow reduces its effectiveness. This is because cooling is efficient when the drops evaporate in the flame or on the surface of the material. Drops of smaller diameters partially evaporate before they reach the flame zone, and some of them also do not reach it by the action of the aerodynamic resistance and convection. It has been suggested that there is an optimal size of drops to extinguish the fire. It is difficult to find this value because there are different objectives of these explorations. In theory, quite simply is to determine the optimal size. It is significantly more complicated in real situations where the spray stream must face several impeding factors during injection it to hostile mass of fire hot gases. The smaller the droplet is, the better the cooling capacity is, but if the drops are too small then it is likely that interacting with the flames preventing the drops to reach the source of the fire. This loss of water to the environment is particularly important if and only if the ultimate goal is putting out the fire source using the spray stream. In terms of cooling gas phase, this effect is no longer so important, and the size of drops in the stream may be reduced. Commonly accepted fact is that stream sprayed with an average diameter of equal to 350 mikronom (0.35 mm) is ideal to apply it to cool the gaseous phase (Kaleta, 1985; Wilczkowski, 1995).

Water stream consisting of drops which diameter is included in the size range from 1 mm to 3 mm is commonly called spray jet. When there is only the possibility to come up to the fire for a proper distance that allows the use of a distributed stream, we should use it because it has better firefighting properties than solid jet. The spray stream does not have so much kinetic energy as the solid one, but it does not cause damage to breaking and shifting of extinguished objects. Water stream distributed in a fire zone, falling as rain has a large cooling effect on the combustion products. Spray jet covers more surface than the solid one. Structure of this jet facilitates evaporation of water, and thus more heat absorption and strong saturation fire atmosphere by water vapour, which in turn causes a reduction of the oxygen concentration in the room during fires. Spray jets are applied everywhere, where there is no need to use solid jets, especially during the extinguishing of the surface of wooden structures, fibrous materials, shredded or loose. It is also applied to gradual cooling of the strongly warmed surface of construction structure, which could be deformed, damaged and collapsed by the rapid cooling using solid jets. They are also applicable to cooling of the surface of tanks with flammable liquids (Wilczkowski, 1995). Generally it is assumed that the mist stream is a stream of water with drops of about the size of 0.1 mm to 1 mm. However, given the values, as in the case of spray jets are only contractual values, because in Poland there is no standard, which would accurately determine this parameter. Therefore, by describing the type of the stream produced we mean more same effect, obtained by applying a particular stream, than precise numerical values. Mist stream has similar properties and use as spray stream, with the fact that the process of receiving heat from a fire is repeated in relation to the other jets. Unfortunately, this is done at the expense of reducing the average length of a stream and though it is a partially eliminated in that it produced a cloud of water mist cools the products of combustion, fireman must approach very close to the fire source to effectively carry out firefighting operations. The mist jet is suitable for extinguishing flammable liquids lighter than water, which is not allowed in any respect, extinguish streams likely to throw liquid burning compact and contribute to the spreading of fire (Wilczkowski, 1995).

For the supplying of jets water nozzles are used, which due to the design can be divided into standard and universal. Standard nozzles are mainly used for supplying of solid jets, but thanks to mist heads it is also possible to produce spray jets. Their disadvantage is the inability to use during fires in closed spaces. The second type of nozzles nozzles are universal, now most commonly used. Water nozzles type "Turbo", popularly called "turbojets" are equipped with rack-and-pinion turbine breaking outflowing stream of water. The capacity and angle of the water stream can be easily adjusted by the change of nozzle set. They have an ergonomic design so that you can quickly change the parameters of the spray jet. They work on the principle of pressure spraying water. Universal nozzles are equipped with a whirl ring at the outlet. It sprays a stream of water, and in addition enables to create a rotational move of the stream. Water nozzles type "Turbo" are the end of both low as well as high pressure hose lines. Such a line enables to generate either solid or spray jets. Using the appropriate type of universal nozzle it is also possible to obtain both jets simultaneously. Nozzles type "Turbo", due to the possibility of making different sorts of water streams, have a wide range of applications. One of them is the suppression of internal fires, and especially protection against very danger phenomena like flashover and backdraft. Water nozzles are basic equipment, which the firefighters use during the action. However, in order to effectively utilize its capabilities, one must know the basic techniques for manipulating streams. Nozzles "Turbo" give the ability to produce highly scattered streams, which have very good properties of heat receiving. The technique of supplying of these streams by nozzle "Turbo" consists of giving of small drops of water to the hot upper layer of compartment, using a series of short "shots" (the techniques of pulsatile supplying of water). Pulsatile supplying of water is performed by quickly opening and closing the valve lever of the nozzle. In the ideal case, the individual "shots" should take from 0.1 - 0.5 seconds, in order to penetrate properly the upper layer of the room with mixture of small drops of water. Evaporated water will cause cooling and dilution of the thermal decomposition products. As a result, it will not allow continuing the fire spreading. "Shots" lasting longer than a second will contribute to the sudden going down of hot gases layer, what could cause firefighters burning. There is also the same danger in the case when unevaporated water collects on the ceiling and falls in the form of hot drops. The second important element affecting the effective use water stream produced by nozzle "Turbo" is a valid setting of the nozzle. Optimal cone angle is 60°, and inclination angle (angle between the ground plane and nozzle axis) is 45° (Mawhinney and Solomon, 1996). This setting is associated with the volume of produced "the cone", which is approximately 16 m^3 and closely associated with the volume of fire gases cooled. These are preferred values, which in fact are changed depending on the encountered situations (e.g.: the size of the room). Therefore, it is required to thoroughly understand the goals and capabilities of this technique by firefighters. In addition, a firefighter must have some experience in pulsed-giving water, and such skills can get only during regular exercise to be carried out in special smoke chambers (Kaleta, 1985).

One of the significant parameters of the fire efficiency is the amount of heat received by the spray given by the nozzle. Part of computer fire models contains more or less accurate extinguishing submodels, but they simulate only fixed extinguishing systems such mist nozzles or sprinklers (Jones et al., 2005; MGrathan, 2006; Nelson, 1990; Novozhilov et al., 1997; Novozhilov, 1999; NFPA, 2000). In the literature of the world is very difficult to find publications that involve extinguishing models using water nozzles. One of them is the thesis containing extinguishing model using pulsatile jets produced by turbo nozzles (Suslavicius, 2011). A study on extinguishing model using solid or spray stream produced by the nozzle has been carried out at The Main School of Fire Service in recent years. The primary objective of this research was to study the influence of the nozzle settings on the extinguishion efficiency. The ability to operate a change of the degree of dispersion, capacity, location and inclination angle of the nozzle allowed to determine their impact on the possibility of cooling by spray stream. The study was conducted with the help of computer simulation in a special program called "Q_g". It uses water extinguishing model using modern water nozzles. The results obtained were compared with the data concerning the effectiveness and application of spray streams for the purposes of fire extinguishing. They also have made it possible to evaluate the changes in the values of the received heat using different settings of the nozzles of type “turbo”.

Materials and methods

Physical and mathematical model of cooling process

The following assumptions were included in the model:

1. Cooling of upper layer can be carried out only with the help of spray and mist jets. The use of solid jet for cooling of this layer is considered to be an error of the rescuer and the development model of fire does not take this process into account.
2. It is assumed arbitrarily that the inclination angle of the nozzle should be smaller than the arctg ((Z-1)/3). If the inclination angle will be greater,

this means providing water to the upper smoke area, which position is determined by the height of *Z*.

3. The influence of different diameters drops in a stream on the cooling process has been neglected. The average diameter of the drops for solid jet greater than 3 and less than 5 mm, spray jet greater than or equal to 1 mm and less than 3 mm, and mist jet greater than or equal to 0.1 mm and less than 1 mm, have been assumed. After selecting the type of the jet average diameters of drops will be drawn with the same probability within the established ranges diameter.
4. The angle of the spray flow in the range from 20° to 90° for spray jet, and in the range from 91° to 120° for mist jet was adopted. This angle is related to the average diameter of a drop in such a way that the smaller the diameter of the larger angle (Gil and Placek, 2003).
5. Capacity of the nozzle can be a constant or variable depending on its type. In the case of nozzle Turbojet52 capacity can be adjusted in the range from 100 to 400 dm^3/min (Gil and Placek, 2003).
6. Track of either solid stream or a single drop is consistent with the ballistic curve equation, and its section is a circle with a diameter equal to the diameter of the nozzle-tip. The influence of interaction of the stream on the shape of its track was neglected.
7. An arbitrary value of the extinguishing efficiency coefficient $0 < K_g < 1$, which takes into account, among others, the loss of the stream in the way nozzle-upper layer, mutual interaction of droplets in a stream of droplets, diversity of drops diameter, change the diameter of the drops due to evaporation. In the first approximation $K_g = 0.6$ was assumed.
8. No external impacts on stream compact, e.g. wind or back blowing distorting track of drops was assumed.
9. All drops have the same speed as to the direction and values.
10. Constant temperature of drops and the upper layer was assumed.
11. The heat is received by convection and by heating and evaporating the water drops coming to the upper layer.
12. The same average diameter of evaporating drops was assumed.
13. The influence of extinguishing process on pyrolysis was not considered.
14. Drop evaporation coefficient K_p for spray and mist jets cooling upper layer was adopted. It is equal to the ratio of the quantity of drops completely vaporized to the quantities of all the drops penetrating the upper layer. In the first approximation $K_p = 0.5$ was assumed.
15. Changes in diameter of droplets as a result of its partial evaporation were not considered.
16. The speed of all outlets drops either spray or mist stream are the same.
17. The average speed of a central stream flowing out the nozzle under the angle β was given to determine the number of Reynolds.

A diagram of the cooling of the upper layer using the spray or mist jet is shown in Fig. 1.

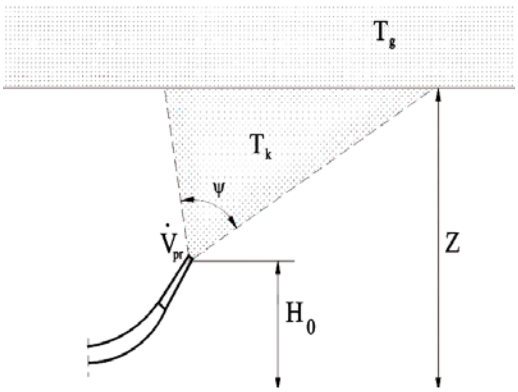

Fig. 1 A diagram of upper layer cooling using spray or mist jet

The value of heat received from the upper layer by spray or mist jet can be presented in the form of the following relationships:

$$\dot{Q}_g = 6 \cdot K_{s1} \cdot \dot{V}_{pr} \cdot \left[\begin{array}{l} K_g \cdot Nu \cdot \lambda \cdot \left(T_g - T_k\right) / \delta_0^2 + \\ + 6 \cdot K_p \cdot \dfrac{dm_k}{dt} h_v / \left(\pi \cdot \delta_0^3\right) \end{array} \right] \quad (1)$$

where:

$$\rho_s = 0,5 \cdot \left(\rho_g + \rho_k\right) \quad (2)$$

$$T_s = 0,5 \cdot \left(T_g + T_k\right) \quad (3)$$

$$\nu = 17,08 \cdot 10^{-6} \cdot \frac{T_s\left(273 + C\right)}{273 \cdot \rho_s \cdot \left(T_s + C\right)} \sqrt{\frac{T_s}{273}} \quad (4)$$

$$\lambda = 0,024 + (T_s - 273) \cdot 6 \cdot 10^{-5} \quad (5)$$

$$B = w_0^2 \cdot \sin^2 \beta - 2 \cdot g \cdot \left(Z - H_0\right) \quad (6)$$

$$\tau_3 = \left(w_0 \cdot \sin\beta - \sqrt{B}\right)/g \qquad (7)$$

$$w_{xg} = w_0 \cdot \cos\beta \qquad (8)$$

$$w_{zg} = w_0 \cdot \sin\beta - g \cdot \tau_3 \qquad (9)$$

$$w_{sg} = \sqrt{w_{xg}^2 + w_{zg}^2} \qquad (10)$$

$$Re = \frac{w_{sg} \cdot \delta_0}{\nu} \qquad (11)$$

$$Nu = 2 + 0,6 \cdot Re^{1/2} \cdot Pr^{1/3} \qquad (12)$$

$$\frac{dm_k}{dt} = 2\pi \cdot \delta_0 \cdot \lambda \cdot \ln\left[1 + c_p \cdot \left(T_g - T_w\right)/h_v\right] \cdot \cdot\left(1 + 0,3 \cdot \sqrt{\mathrm{Re}} \cdot \mathrm{Pr}^{0,33}\right)/c_p \qquad (13)$$

$$K_{s1} = \begin{cases} 0 \quad \text{dl } \left(\text{Z-H}_0\right)/\text{tg}\left(\beta + 0,5 \cdot \psi\right) > \\ > \text{L}_\text{p}\text{-x}_\text{p} \ \cap \ \left(\text{Z-H}_0\right)/\text{tg}\left(\beta + 0,5 \cdot \psi\right) > \text{W}_\text{p}\text{-y}_\text{p} \\ \cos\left(0,5 \cdot \pi\text{-}\beta\right) \quad \text{for other cases} \end{cases}$$

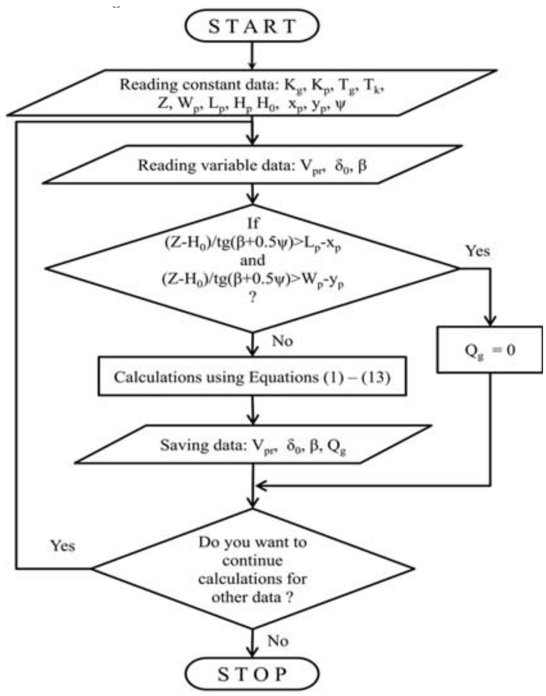

Fig. 2 A block diagram of the algorithm corresponding to the cooling of the hot upper layer by sprays or mist jet

Computer simulation of cooling process

In order to perform the calculations for the program, the following input data should be entered:

a) type of the nozzle,
b) type of jet (spray, mist),
c) solid angle of the spray ψ [rad],
d) the average droplet diameter δ_0 [mm],
e) nozzle capacity $\dot{V}_{pr}$ [dm^3/min],
f) diameter of nozzle-tip d [mm],
g) inclination angle of the nozzle β [rad],
h) coordinate of the nozzle base along axis Ox - x_p and Oy - y_p,
i) the height H_0 of the nozzle-tip position in relations to the floor [m],
j) length L_p and width W_p of the compartment [m],
k) time of extinguishing start τ_g [sec],
l) droplet temperature T_k [K],
m) ambient temperature T_o [K],
n) upper layer temperature T_g [K],
o) vertical position of upper layer Z [m].

A block diagram of the algorithm corresponding to the cooling of the hot upper layer by spray or mist jet is shown in Fig. 2.

After the introduction of the input data in the subsequent steps, program checks the condition of reaching the stream to the upper layer. If a spray reaches the hot zone, the stream of heat received is calculated according to the formula specified in the block. Otherwise, the value of this heat is reset to zero.

The subject of the simulation was the process of upper layer cooling with water using a spray jets. Many calculations loops were carried out for different values of the capacities and inclination angle of the nozzle as well as average droplet diameters.

The following fixed values were adopted:

a) compartment length L_p = 5 m,
b) compartment width W_p = 5 m,
c) compartment height H_p = 3 m,
d) solid angle of the spray $\psi = \pi/2$ rad,
e) coordinate Ox of the nozzle-tip x_p = 2 m,
f) coordinate Oy of the nozzle-tip y_p = 2 m,
g) coordinate Oz of the nozzle-tip H_0 = 1 m,
h) height of the upper layer Z = 2.5 m,
i) droplet temperature T_k = 288 K,
j) upper layer temperature T_g = 473 K,
k) extinguishing effectiveness coefficient K_g = 0.6,
l) evaporation coefficient K_p = 0.5.

The following different variants of values in calculation loops were adopted:

a) nozzle capacity $\dot{V}_{pr}$ = 200 or 400 dm^3/min,
b) average droplet diameter in spray and mist stream δ_0 = 0.1 or 0.3 or 0.4 or 0.5 or 0.6 or 0.8 or 1.0 mm,
c) inclination angle of the nozzle β = 30 or 45 or 60 or 90 deg.

Results

In this part of the work the selected results obtained during simulation and their analyses have been presented. The graphs of the heat receive rate at nozzle capacities V_{pr} = 200 dm^3/min and V_{pr} = 400 dm^3/min and at a constant angle of its inclination equal to 45 deg were shown in Fig. 3. Increasing the output twice, heat flux received by the spray increased nearly three times for all droplet diameters. The value of the received heat rises along with a reduction in the diameter of the droplet. Between diameters of 0.3 mm and 1 mm decrease in extinguishing effectiveness was observed (decrease received heat values). However, with diameters less than 0.3 mm, amount of heat receive rate is growing rapidly. At a diameter of 0.1 mm the values of about 132 MW for the output V_{pr} = 400 dm^3/min and 50 MW for the output V_{pr} = 200 dm^3/min were achieved. When droplet diameter changes from 0.3 mm to 0.1 mm over five times increase of heat receive rate can be noticed. It is comparable with those which occur when you change the diameter of the drops from 1 mm to 0.3 mm.

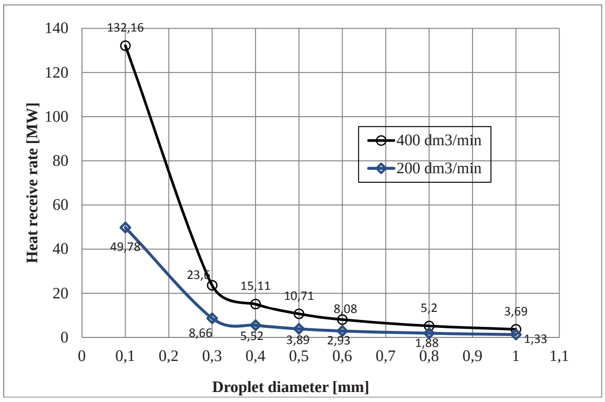

Fig. 3 Heat receive rate versus droplet diameter for two different outputs V_{pr} = 200 dm^3/min and V_{pr} = 400 dm^3/min and inclination angle β = 45 deg

The relationship between the heat receive rate and droplet diameter as well as inclination angle for two outputs V_{pr} = 200 dm^3/min and V_{pr} = 400 dm^3/min are shown in three-dimensional coordinates system in Fig. 4 and 5.

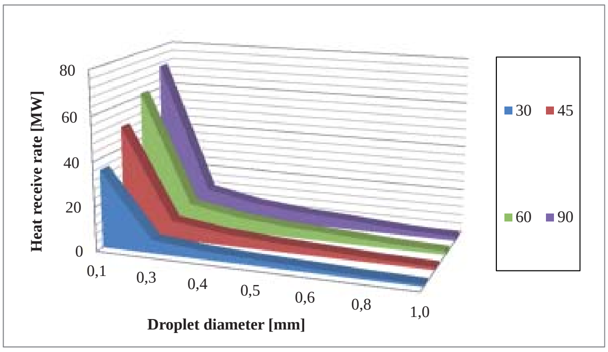

Fig. 4 Heat receive rate versus droplet diameter for nozzle output V_{pr} = 200 dm^3/min

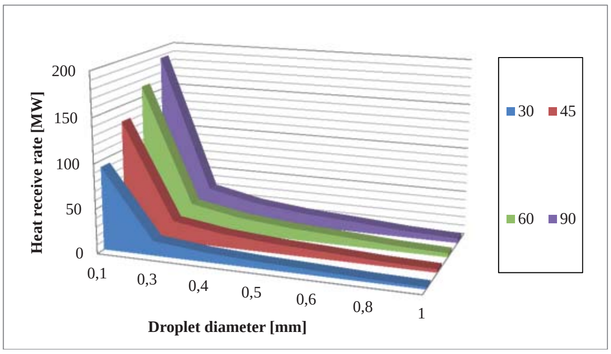

Fig. 5 Heat receive rate versus droplet diameter for nozzle output V_{pr} = 400 dm^3/min

With either increase of inclination angle or nozzle output, the amount of water reaching the upper layer (hot zone) increases. This resulted in the increase of heat received from the upper layer. As in the previous analysis, there has been a great increase in the amount of heat received by droplets diameters of less than 0.3 mm.

Another advantage of simulation experiment was the ability to use a wide range of angles of the nozzle inclination. Hot gases quickly and in large quantities accumulate under the ceiling of the room where the fire develops. Even little accurate pointing of the stream into the upper zone, resulting in a quick and efficient cooling by receiving a large quantities of heat from the hot zone.

The values of heat receive rate at different inclination angle of the nozzle and droplet diameters for constant output V_{pr} = 200 dm^3/min were included in Tab. 1.

Tab. 1 The values of heat receive rate for output V_{pr} = 200 dm^3/min

β [deg] / δ_0 [mm]	30	45	60	90
0.1	35.00	49.78	61.09	70.43
0.3	6.10	8.66	10.63	12.26
0.4	3.88	5.52	6.77	7.80
0.5	2.74	3.89	4.78	5.51
0.6	2.06	2.93	3.60	4.15
0.8	1.32	1.88	2.30	2.66
1	0.93	1.33	1.63	1.88

The most effective location was angle β = 90 deg at the diameter of a drop of δ_0 = 0.1 mm. For these parameters heat receive rate reached a value of Q_g = 70.43 MW. The largest increase in the extinguishing effectiveness depending on the inclination angle between β = 30 deg and β = 45 deg has been observed, while the most efficient cooling of the upper layer occurs at the diameter of a drop of δ_0 = 0.1 mm. In turn, the most unsuitable nozzle settings correspondwere to angle β = 30 deg and the diameter of a drop of δ_0 = 1 mm. For these parameters the value of heat receive rate is equal to Q_g = 0.93 MW. Summary of the results obtained, clearly indicates that the greatest influence on the effectiveness of upper layer cooling has the degree of stream fragmentation.

The values of heat receive rate at different inclination angle of the nozzle and droplet diameters for constant output V_{pr} = 400 dm^3/min were included in Tab. 2.

Tab. 2 The values of heat receive rate for output V_{pr} = 400 dm^3/min

β [deg] / δ_0 [mm]	30	45	60	90
0.1	92.90	132.16	162.19	186.97
0.3	16.59	23.60	28.96	33.39
0.4	10.62	15.11	18.54	21.38
0.5	7.52	10.71	13.14	15.15
0.6	5.68	8.08	9.92	11.44
0.8	3.65	5.20	6.38	7.35
1	2.59	3.69	4.53	5.22

Similarly as for the output V_{pr} = 200 dm^3/min, value of heat receive rate increase with the reduction of the diameter of the droplets and increase of inclination angle. The value of maximum and minimum also occurred in similar settings prądownicy (Q_g = 186.97 MW for δ_0 = 0.1 mm and β = 90 deg and Q_g = 2.59 MW for δ_0 = 1 mm and β = 30 deg).

Conclusion

Thanks to computer simulation of upper layer cooling model carried out in The Main School of Fire Service, influence of inclination angle of the nozzle, droplet diameters and output of the nozzle on the value heat flux received from upper layer can be studied. High cooling effectiveness of the upper layer by the spray in comparison with other type of jets produced by current nozzles can be concluded.

On the basis of the results obtained during the simulation tests the following conclusions can be formulated:

1. From cooling effectiveness point of view (the highest vale of heat receive rate) the best parameters obtained during simulation tests are: β = 90 deg, δ_0 = 0.1 mm and V_{pr} = 400 dm^3/min. For these parameters Q_g = 186.97 MW. At the same average diameter of drops and less output V_{pr} = 200 dm^3/min, Q_g = 70.43 MW.
2. The smallest cooling effectiveness among tested scenarios was obtained for the following parameters: β = 30 δ_0 = 1 mm and V_{pr} = 200 dm^3/min. For these parameters Q_g = 0.93 MW, which is up more than 75 times lower compared to the most efficient stream.
3. Cooling model described in the paper enables to estimate the required parameters of the water jet spray (spraying intensity, the average diameter of drops), which will be held on the efficiency needed to cool the upper layer.
4. Wider use of mist jets by firefighters during internal fires is yet limited, because intensive cooling of hot gases, together with effective heat removal gives a very large volume of water vapour. Its accumulation leads to a „piston effect“, which threatens the health and life of the rescuers.
5. The results obtained in the form of a stream of heat received should be validated experimentally. This can be a problem, because the direct measurement of this stream is impossible, and indirect measurement through observations of the changes in temperature of upper layer will be characterized by large errors. However, despite these difficulties, the application of the proposed model seems to be intentional, to study at what nozzle inclination angle, doplet diameters and nozzle output cooling of upper layer is most satisfied.
6. It seems to be intentional to apply a similar model to the study of extinguishing process using the solid or spray jet given directly to the combustion zone. Currently research into such a simulation model are provided.

Systematic development of extinguishing models of the fires with the help of the nozzles is intended in the coming years by.

a) integrating the different diameters of droplets and their statistical distributions,

b) coupling of extinguishing model coupling with the hybrid fire model,

c) taking into account of the changes in droplets diameter due to evaporation.

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