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Experimental Study of Hydro-aerosol Cooling of Sausages: Effect of the Process Factors on the Cooling Intensity

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ABSTRACT

The objective of the paper was the controllable hydro-aerosol cooling process of scalded and smoked sausages and the effect of the main process factors on the cooling intensity to be studied. The hydro-aerosol medium includes water droplets dispersed in moist air. The total cooling time, cooling rate and surface heat-transfer coefficient were used as indexes for estimating the heat-transfer intensity. The order of the studied process factors ranked by their significance is the following: sausage diameter (1·62), cooling water temperature (0·14), air-flow velocity (−0·10) and air-flow temperature (0·10). Sensitivity functions are pointed between briskets and they show the change of an intensity index caused by a unit variation of a process factor. The intensity of the studied controllable hydro-aerosol cooling is 1·4–3·8 times higher than the cooling at industrial conditions. The hydro-aerosol cooling can ensure the production of safety, high quality sausages with natural and synthetic covers and their shelf-life to be prolonged. © 1998 Elsevier Science Limited. All rights reserved

NOMENCLATURE

$\mathrm{Bi} = h^*(d/2)/k$	The modified number of Biot
c, k, ρ	Specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$), thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$) and density ($\mathrm{kg\,m^{-3}}$) of sausage
d	Sausage diameter (mm)
F_c	Cross-section area of the experimental chamber ($\mathrm{m^2}$)
F_s, V_s	Heat-transfer surface ($\mathrm{m^2}$) and volume ($\mathrm{m^3}$) of the sausage studied

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G_w	Mass flow rate of cooling water (kg s^{-1})
h^*	Efficient coefficient of surface heat-transfer (W m^{-2} K^{-1})
m	Cooling rate (K s^{-1})
P	Perimeter (girth) of the cross-section of a sausage (m)
t, t_{rg}	Actual cooling time and the beginning of regular cooling regime (min)
t_t	Total time of cooling (min)
T_a	Temperature of air flow before mixing with cooling water (°C)
T_{cm}	Temperature of cooling medium (°C)
T_{sc}	Temperature of sausage centre (°C)
T_w	Temperature of cooling water (°C)
T_{wf}	Temperature of water film on the surface of sausage (°C)
w_a	Velocity of air flow (m s^{-1})
$\Gamma = G_w P / F_c$	Specific watering intensity by the nozzle (kg m^{-1} s^{-1})
$\Phi'_f = (\partial I/I)/(\partial f/f)$	Sensitivity function of the intensity index I (t_t, m, h^*) concerning the factor f (d, T_w, w_a, T_a)
φ_a	Relative humidity of air flow (%)

INTRODUCTION

Thermal processing of scalded and smoked sausages includes consequent heating and cooling. The temperature of the sausage centre at the end of heating must reach 75°C and, at the end of cooling -15°C (Karmas, 1977; Kostov, 1987). The quick cooling from 55 to 15°C can prevent the growth of micro-organisms and assure the safety and quality of the processed sausages (Heilmann, 1988). Air, water cooling, their combination and modifications are widespread in the meat industry. The main disadvantage of these methods is the long cooling time. The considerable weight losses (>5%) of sausages and the high value of cooling water consumption are some of the additional disadvantages of the air and water cooling, respectively (Reichert & Thumel, 1988).

Hydro-aerosol cooling enables the thermal processing of sausages to be intensified (Tantikov, 1982; Kurako, 1987; Kalinitchenko *et al.*, 1989). The hydro-aerosol medium embraces moist air (the medium of dispersion) and fine water drops (the phase dispersed). Special water-spraying nozzles generate the water droplets which size is in the range of 100–200 μm (Reist, 1987; Kalinitchenko *et al.*, 1989). Semilet (1961), Isatchenko *et al.* (1965), Vorontzov and Tanaiko (1972) established that the continuos water film on the sausage surface ensures a continuous evaporation of water (Kokorin, 1965; Tocci & Mascheroni, 1995) and a high intensity of heat transfer carried out by conduction, convection and evaporation. On the other hand, the continuous water film reduces the weight losses of sausages below 1% (Tantikov, 1982; Kurako, 1987; Kalinitchenko *et al.*, 1989). Semilet (1961), Kokorin (1965), Isatchenko *et al.* (1965), Vorontzov and Tanaiko (1972), Grezitza (1985), Tocci and Mascheroni (1995) showed that the adiabatic cooling additionally enhances the cooling rate due to a continuous evaporation.

According to the literature survey, the following conclusions were done: the diameter (d) of sausage, the temperature (T_w) of cooling water, the velocity (w_a) and the temperature (T_a) of air flow, the specific watering intensity (Γ) are the most affecting process factors. Vorontzov and Tanaiko (1972), Tantikov (1982), Radespiel *et al.* (1983), Heilmann (1988), Kalinitchenko *et al.* (1989), Tocci and Mascheroni (1995) obtained that the temperature of cooling water below 10°C considerably decreases the total time of cooling. Radespiel *et al.* (1983), Kalinitchenko *et al.* (1989) determined that the subzero temperatures ($T_a < 0$°C) of air flow causes an ice film on the sausage surface to be formed. This ice film wrinkles the sausage cover and causes deterioration in the appearance and quality of sausages processed. Andreev (1985) and Olevskii (1988) found that the velocity (w_a) of air flow > 1 m s^{-1} intensifies the convective heat transfer between the water film and air flow. On the other hand, the velocity (w_a) < 4 m s^{-1} prevents the small water droplets to be carried away and allows the water film to flow down by gravitation. The latter velocity regime assures a continuous water film to be maintained. Semilet (1961) and Vorontzov and Tanaiko (1972) specified that the minimum watering intensity should be in the range of $\Gamma = 0{\cdot}0041$–$0{\cdot}061$ kg m^{-1} s^{-1}. This minimum watering intensity ensures a continuous water film on the sausage surface. The pointed low and high Γ-values correspond to the surface temperature of sausage equal to 15 and 75°C, respectively. The thickness of the water film is in the range of 0·3–0·45 mm.

The objective of this work was to determine the effect of the process factors: sausage diameter; the cooling water temperature; the velocity and the temperature of air flow on the intensity of the cooling process.

MATERIALS AND METHODS

Scalded and smoked sausages including pork, beef, salt and spices were used for the study. Four kinds of sausages with the following diameters/lengths 80/400, 60/400, 40/280 and 30/230 mm produced according to Bulgarian State Standards BDS 3055-83 and BDS 127-83 (Bulgarian State Standard, 1983a, 1983b) were studied. The following average values of the thermo-physical characteristics of sausages were established: density 1014 kg m^{-3} ($C_v = 0{\cdot}2\%$), specific heat capacity 3122 J/(kg K) ($C_v = 3{\cdot}8\%$), thermal conductivity 0·47 W/(m K) ($C_v = 3{\cdot}0\%$), thermal diffusivity $1{\cdot}48 \times 10^{-7}$ m^2 s^{-1} ($C_v = 0{\cdot}02\%$). These data correspond to the following average values of water content 62% ($C_v = 1{\cdot}9\%$); fat 68·7% ($C_v = 1{\cdot}0\%$) and protein 20·7% ($C_v = 0{\cdot}9\%$) contents in the dry substance of sausages, respectively. The coefficients-of-variation for the corresponding quantities are shown between the parentheses. Peleev *et al.* (1970), Fikiin (1980) and Tantikov (1982) obtained that the thermo-physical characteristics of sausages can be accepted as constants in the temperature range of 15–80°C. Taking into consideration the above-mentioned conclusion and the present results, it was assumed that the thermo-physical characteristics of the sausages studied have constant values in the temperature range studied.

The schematic diagram of the used research unit (Georgieva, 1990) is presented in Fig. 1. This unit enables the main process factors (T_w, T_a, w_a) to be controlled in a larger range. The cooling water is dispersed by the standard nozzle 'FULJET TG-8W' of Spraying Systems Co (Wheaton, IL, USA). The disposition of the nozzle lower than the sausage processed and the forward-current of air and water drops' flows is the original element of experimental unit. This configuration enables the temperature of water film on the sausage surface to vary in a narrower range and to be approximately equal to the temperature of cooling water.

The temperature of cooling water (T_w) and air-flow (T_a) were controlled by heat-exchangers and measured by mercury-in-glass thermometers. The velocity (w_a) of air flow in the hydro-aerosol chamber was controlled by the fan speed and measured by the anemometer Testoterm. The temperature of sausage centre (T_{sc}) was measured by thermocouples. The flow-rate (G_w) of cooling water was controlled by a water cock and measured by a water flowmeter. The temperature of cooling medium (T_{cm}) and the relative humidity (φ_a) of air flow were not controlled. These two factors were only monitored by means of the wet-bulb of a psychometer and Haarhygrometer, respectively.

According to the conclusions found by literature survey, the studied process factors vary in the following ranges specified: temperature of cooling water $T_w = 1$–$5°C$; temperature of air flow $T_a = 5$–$15°C$; velocity of air flow $w_a = 1$–$4\ m\ s^{-1}$. All experiments were carried out with constant flow rate (G_w) values and the pressure of cooling water. The corresponding watering intensity is equal to $\Gamma = 0{\cdot}063$; 0·082; 0·123; 0·164 kg $m^{-1}\ s^{-1}$ for the sausages with diameters 30; 40; 60 and 80 mm, respectively. These intensities ensure a continuous water film on the sausage surface.

The following quantities were used as indexes for comparing the heat-transfer intensity at the hydro-aerosol cooling:

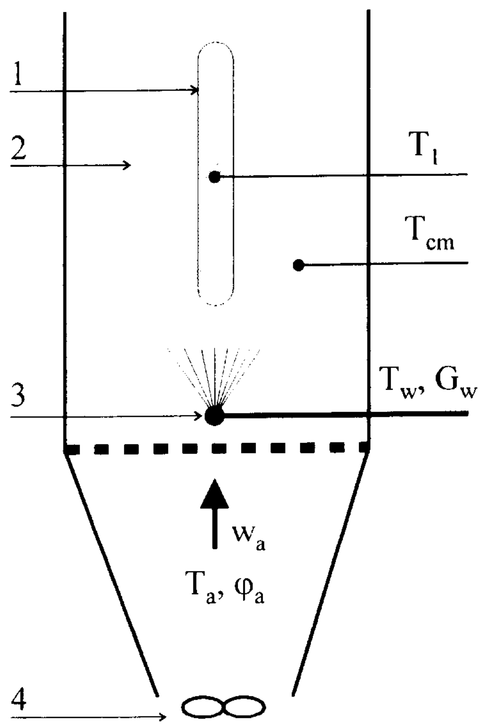

Fig. 1. Schematic diagram of the experimental unit used. 1, Sausage cooled; 2, hydro-aerosol chamber; 3, water-spraying nozzle; 4, fan.

(1) The total time of cooling (t_t) is the widely used index in practice (Radespiel *et al*., 1983). This index represents the time for which the temperature of sausage centre (T_{sc}) drops from 75 to 15°C.

(2) The cooling rate (m) is determined by the following relationship (Kondratev, 1954; Tcherpakov, 1975)

$$m = -\frac{\Delta \ln(T_{sc} - T_{cm})}{\Delta t} \tag{1}$$

The straight part ($t > t_{rg}$) of the diagram temperature difference $\ln(T_{sc} - T_{cm})$ versus the actual time t of cooling (Fig. 2) is related to the regular regime of cooling. The cooling rate (m) corresponds to the slope of the above-mentioned linear part.

(3) The efficient coefficient of surface heat-transfer (h^*) was evaluated by the relationship

$$h^* = \frac{mc\rho V_s}{F_s} \tag{2}$$

This index is widely used in thermodynamic practice (Kondratev, 1954; Isatchenko *et al*., 1965; Tcherpakov, 1975). This coefficient was determined as efficient because

(i) it summarizes the heat-transfer intensity realised by conduction, convection and evaporation;

(ii) the cooling process is not stationary and the sausage temperature is not uniform.

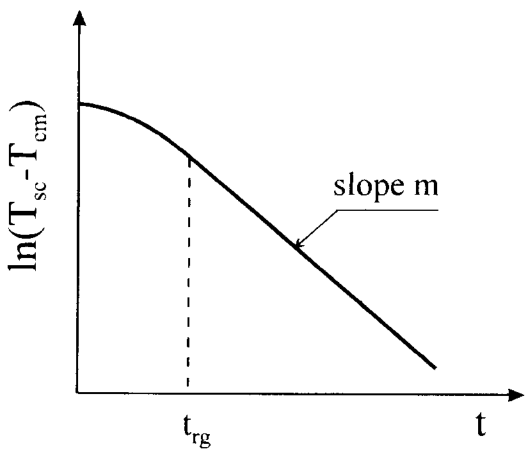

Fig. 2. Temperature penetration curve in a semi-logarithmical graph. The straight part of the curve ($t \geq t_{rg}$) is related to a regular regime and the rest to an irregular regime.

The significance of the process factors was evaluated by the set of sensitivity functions. The sensitivity function $\Phi_f^I = (\partial I/I)/(\partial f/f)$ represents the change in an intensity index I (t_t, m, h^*) caused by a unit variation of a process factor f (d, T_w, w_a, T_a).

RESULTS AND DISCUSSIONS

The results of the experimental study and the corresponding conditions of the studied regimes are presented in Table 1. Each experiment was repeated three times and the adequacy of experiments was confirmed. The values shown in Table 1 are averages.

The studied process factors were ranked by sensitivity functions evaluated by the effect of each process factor on the total time t_t of cooling:

(1) sausage diameter: $\Phi_d^t = 1{\cdot}34\ \underline{1{\cdot}62}\ 2{\cdot}14$ ($C_v = 12\%$)
(2) temperature of cooling water: $\Phi_{T_w}^t = 0{\cdot}08\ \underline{0{\cdot}14}\ 0{\cdot}21$ ($C_v = 26\%$)
(3) velocity of air flow: $\Phi_{w_a}^t = -0{\cdot}03\ \underline{-0{\cdot}10}\ 0{\cdot}26$ ($C_v = 54\%$)
(4) Temperature of air flow: $\Phi_{T_a}^t = 0{\cdot}02\ \underline{0{\cdot}10}\ 0{\cdot}35$ ($C_v = 72\%$)

The underlined values are the median of the corresponding sensitivity functions. C_v represents the coefficient of variation for the corresponding sensitivity functions.

According to the pointed ranked order of the process factors, the following conclusions can be done: the sausage diameter (d) is the most important process factor whose level of significance is at least one decimal order higher than the significance of the rest factors. The temperature of the cooling water (T_w) is the most important controllable factor. On the basis of the sensitivity-function definition, the following relationship can be derived

$$\frac{\Delta T_w}{T_w} = -\left(\frac{\Phi_d^t}{\Phi_{T_w}^t}\right)\left(\frac{\Delta d}{d}\right) \text{ or } \frac{\Delta T_w}{T_w} = -11{\cdot}6\left(\frac{\Delta d}{d}\right)$$

in the case of average conditions

This simple relationship can cause the cooling water temperature T_w to be easily re-calculated in the case of a change of the sausage diameter d (the kind of the sausage processed).

The applicability of the intensity indexes was assessed by sensitivity functions which evaluated the effect of the most affecting factor—sausage diameter—on the following indexes:

(1) Total time of cooling: $\Phi_d^t = 1{\cdot}34\ \underline{1{\cdot}62}\ 2{\cdot}14$ ($C_v = 12\%$)
(2) Cooling rate: $\Phi_d^m = -0{\cdot}25\ \underline{-1{\cdot}39}\ -6{\cdot}00$ ($C_v = 64\%$)
(3) Efficient coefficient of heat-transfer: $\Phi_d^h = -2{\cdot}32\ \underline{-0{\cdot}51}\ +1{\cdot}00$ ($C_v = 143\%$)

The results obtained unambiguously show that the total time (t_t) of cooling is the most suitable index. Equation (2) for assessing the efficient coefficient (h^*) of convection heat-transfer is not adequate enough to evaluate the hydro-aerosol cooling intensity.

TABLE 1
Summarized Results of the Experimental Study

Regime index	*Experiment conditions*					*Indexes of heat-transfer intensity*		
	T_w (°C)	T_a (°C)	w_a ($m\ s^{-1}$)	Φ_a (%)	T_{cm} (°C)	t_t (min)	$m \times 10^3$ ($K\ s^{-1}$)	h^* ($W\ m^{-2}\ K^{-1}$)
d = *80 mm*								
1	1	5	1	65	2·4	53	0·83	50·3
2	5	5	1	55	1·7	61	0·71	42·7
3	1	5	3·5	48	1	48	0·97	58·8
4	5	5	3	45	2·2	55	0·87	50·6
5	1	15	1	30	7·4	58	0·95	57·3
6	5	15	1	41	7·7	66	0·89	53·7
7	1	15	3	48	9·5	50	1·04	62·9
8	5	15	3	50	9·7	56	1·02	61·6
8†	5	15	3	62	10·7	60	0·98	59·0
d = *60 mm*								
1	1	5	1	52	1·4	33	1·20	48·1
2	5	5	1	60	2	40	0·94	37·5
3	1	5	3	49	1·2	30	1·27	50·9
4	5	5	3	55	1·5	35	1·17	46·9
5	1	15	1·5	82	12·8	36	2·13	85·3
6	5	15	1	51	9·6	43	1·31	52·5
7	1	15	3	43	8·9	33	1·64	65·7
8	5	15	3	72	9·9	38	1·42	56·9
2†	5	15	1	85	4	44	0·88	35·1
4†	5	5	3	80	3·7	39	0·98	39·3
5†	1	5	1·5	30	7·2	32	1·49	59·7
d = *40 mm*								
1	1	5	1	48	1	15	2·10	50·6
2	5	5	1	75	3·3	19	1·88	45·3
3	1	5	3	51	1·2	12	2·64	64·0
4	5	10	3	52	5·8	16	2·43	58·5
5	1	15	1	30	7·2	17	2·36	56·9
6	5	15	1·5	43	11·2	21	2·57	61·9
7	1	15	2·5	57	10·4	17	3·63	87·5
8	5	15	3	60	10·5	20	2·78	67·0
5†	1	15	1	65	11·1	19	2·97	71·5
7†	1	10	3	78	8·3	18	2·86	68·9
d = *30 mm*								
1	1	5	1	55	1·8	10	3·00	76·3
2	5	5	1	50	1·2	12	2·78	70·7
3	1	10	3	30	3·7	7	4·67	118·7
4	5	10	3	62	6·8	9	4·58	116·5
5	1	15	1	40	8·5	11	3·57	90·8
6	5	15	1	60	10·6	14	3·47	88·2
7	1	15	3	45	9	10	4·17	106·1
8	4	15	2·5	57	10·5	12	3·93	99·9
6†	10	18	1·5	38	10·4	12	4·33	110·4

†These experiments are modified with the air humidity changed. The used quantities are explained in the Nomenclature.

The following additional ascertainments can be noted on the basis of the presented experimental results and additional experiments:

(1) The duration of *total cooling time* is less in the case of lower values of the sausage diameter, the temperature of cooling water, the humidity of air and in other hand a higher value of the watering intensity.
(2) The intensity of *external heat-transfer* can be also evaluated by the modified number Bi = 2·6–7·4. The higher value of Biot number corresponds to higher values of the velocity and temperature of air; a lower value of the water temperature which is less than the temperature of cooling medium (T_{cm}).
(3) The water on the sausage surface can *evaporate* when the temperature of the water film (T_{wf}) is higher than the temperature of cooling medium (T_{cm}). Adiabatic evaporation can be observed when these temperatures are approximately equal. The temperature of the water film (T_{wf}) increases when the temperature of the cooling water (T_w) and the length of sausage are increased and the watering intensity (Γ) is decreased. However, the temperature of water film is difficult to measure and control. For this reason, the temperature differences ($T_w - T_{cm}$) between the cooling water and cooling medium is used the evaporation intensity to be evaluated. When this temperature difference is positive, evaporation continues for the total time of cooling. If the temperature difference ($T_w - T_{cm}$) is negative, evaporation is only observed at the beginning of process when $T_{wf} > T_{cm}$. However, the value of the heat-transfer coefficient (h^*) is higher in the latter case because the convection and conduction heat-transfers are more intensive. Alternatively, the significance of this complex factor—the temperature difference ($T_w - T_{cm}$)—is evaluated by the sensitivity function $\Phi^{h}_{\Delta T} = -0{\cdot}30\ 0{\cdot}10\ 0{\cdot}33$ and is compatible with the other process factors (T_a, w_a). Therefore, the influence of the air humidity on the cooling medium temperature should also be controlled.
(4) The intensity of the studied hydro-aerosol cooling at the controllable experimental conditions was compared with the data of the industrial experiments related to non-controllable hydro-aerosol cooling (Tantikov, 1982; Radespiel *et al.*, 1983; Kurako, 1987; Kalinitchenko *et al.*, 1989) and combined cooling by air and water (Heilmann, 1988). The intensity (evaluated by the indexes t_t, m, h^*) of the controllable hydro-aerosol cooling is 1·4–3·8 times higher than the cooling intensity in non-controllable industrial conditions. The greater effect of the process intensification is observed in the cases of:

    (i) higher values of the sausage diameter (d);
    (ii) higher temperatures of water (T_w) and air (T_a) and a lower velocity of air (w_a).

(5) Hydro-aerosol cooling is applicable for sausages with natural and synthetic covers.
(6) The duration of the irregular phase represents 8–29% of the total cooling time. The higher value corresponds to higher values of the sausage diameter (d) and the temperature differences ($T_w - T_{cm}$) between the cooling water and the cooling medium. The start of the regular regime corresponds to the temperature of sausage centre T_{sc} = 50–55°C.

CONCLUSIONS

The intensity of the studied controllable hydro-aerosol cooling is 1·4–3·8 times higher than the cooling intensity at non-controllable industrial conditions. This cooling process can ensure the production of safe, high quality sausages with natural and synthetic covers and a prolonged shelf-life of sausages. On the other hand, the need for cooling water can be significantly reduced and hydro-aerosol cooling enables the cooling of other food products also to be intensified.

The order of the studied process factors ranked according to their significance is as follows: the sausage diameter; the cooling water temperature; the air flow velocity; and the air flow temperature. The sausage diameter is the most affecting process factor whose significance is at least one decimal order higher than the significance of the rest factors. The cooling water temperature is the most significant controllable factor. In this connection, the proposed simple relationship between the sausage diameter size and the cooling water temperature can be very useful for large scale procedures in engineering practice.

The total cooling time is the most appropriate index for evaluating the hydro-aerosol cooling intensity. The cooling rate is the second most eligible index. The effect of the watering intensity, the air humidity and the length of the sausage needs to be studied further. However, the preliminary results show that the already mentioned first and second factors should be controlled. On the basis of the obtained data, optimal regimes for hydro-aerosol cooling of sausages can be suggested.

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