IMPROVEMENT OF FOOD COOLING UTILIZING FLOW TURBULENCE IN PROPELLER FAN

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ABSTRACT

Propeller fans are widely used in various food production lines. However, only little knowledge is available for the effective cooling of food products using a low-efficiency propeller fans. It is well-known that propeller fans make a highly turbulent flow which can improve the efficiency of heat transfer. This suggests that the propeller fans potentially performed an effective cooling of food products despite of their low fan efficiency if a highly turbulent flow is achieved. In this article, we attempted to obtain detailed data about the characteristics of air flow from propeller fans and the efficacy of heat transfer. The results showed that the maximum flow velocity was found to be high at a position near the propeller fan. Moreover, the flow velocity profile showed a large difference in the vicinity of the propeller fan; whereas, the opposite tendency was found in the farther distance position from the fan.

1. INTRODUCTION

Nowadays, energy saving has become a primary concern in all over the world. In addition, food industries strongly desire for the reduction of energy consumption as to reduce production cost. Propeller fans have been widely used in various food processing mainly because of their easiness of operation rather than their performance. Currently, however, the use of propeller fans to cool cooked food by air flow of room temperature, instead of using refrigerator, is becoming a main focus due to its ability to save energy. This is reffered to as an ambient cooling. In principle, propeller fans have a low fan efficiency that would obstruct the effective energy savings. It is well-known that propeller fans make a highly turbulent flow that is why propeller fans generally have low fan efficiency. Highly turbulent flow, however, possibly improve heat transfer efficiency.

It possibly means that propeller fans can perform an effective cooling of food product despite of their low fan efficiency if a highly turbulent flow was achieved. A large number of researches focused on propeller fan; however, most of them are connecting to noise. There are limited researches on the flow structure and resulted heat transfer characteristics according to Yuan *et al*. (2008).

In this article, we attempted to obtain detailed data about the characteristics of air flow from propeller fans and the efficacy of heat transfer. Furthermore, agarose gel was also studied as a food model to investigate the efficacy of using the propeller fans for an effective food cooling.

2. EXPERIMENTAL PROCEDURE

2.1. Measurement of flow velocity from a propeller fan

We use the pressure propeller fan (TERAL KURITA PF-12BTG diameter 300 mm) which is generally applied to food manufacturing process. Experimental rig, shown in Fig. 1, is made of aluminium frame to support the propeller fan. Hot-wire anemometer (KANOMAX JAPAN INC, MODEL6141) is used to measure flow velocity profile beneath the propeller fan and its output voltage is measured by data logger (HIOKI 8430) at every one second. As seen in Fig. 1, the distance between propeller fan and the measuring point is represented by L, and the radial distance from the center of the fan to the measuring point is represented by r. Coarse metal grid whose mesh size is 50 mm is installed to support the probe of anemometer. The influence of the metal grid installed downward of the anemometer on the accuracy of measured velocity is considered to be negligible by using much coarse grid. The metal grid can be arbitrarily positioned to realize the desired condition for L and r. Main stream direction is defined as vertical downward.

2.2. Measurement heat transfer coefficient

Heat transfer coefficient by the air flow from the propeller fan was measured. The position where the heat transfer coefficient was measured was defined by *L* and *r*, similar to the flow velocity measurement. A sphere made of brass with 30 mm diameter was used to measure the heat transfer coefficient. T-type sheathed thermocouple was fixed at geometrical center of the sphere. Flow temperature was measured at 4 positions and their average was adopted as flow temperature. Since the thermal conductivity of brass is so large that the temperature gradient in the sphere was neglected. Measured temperature was recorded by data logger (ETODENKI, CADAC60) every one second.

2.3. Turbulence intensity measurement

Turbulence intensity of the flow made by propeller fans was measured by using fine hot wire anemometer (KANOMAX JAPAN INC, CTA unit MODEL 1011). On the measurement, output voltage from the probe was first linearized by using linearizer unit (KANOMAX JAPAN INC, MODEL 1013), previously calibrated by calibration unit (KANOMAX JAPAN INC, MODEL 1056, 1066). The linearized voltage was recorded after digitized by AD converter (CONTEC AIO-163202FX-USB) at sampling frequency of 10 kHz.

2.4. Cooling experiment of agarose gel

In order to validate the effect of heat transfer enhancement by propeller fan on food cooling, cooling experiment of agarose gel was performed. The essential difference between metal and food is whether the sample contains a high amount of water; therefore, agarose gel was prepared to be 3 %concentration. Furthermore, the obtained cooling curve was compared with predicted cooling curve by mass dimensional finite difference method.

As shown in Fig. 2, agarose gel was formed in the cylindrical mold of 80 mm diameter and 20 mm in depth made by foam polystyrene to realize one-dimensional heat conduction in the sample. T-type thermocouples of ϕ0.254 mm in outer diameter were fixed at the depth of 1mm and 10mm from the top surface; they are referred to as surface temperature and center temperature, respectively.

The sample prepared as mentioned above were preliminarily heated to 60°C in an incubator (AS-ONE DOV-300P) and were cooled. The temperature was measured to obtain the cooling curve.

3. RESULT AND DISCUSSION

3.1. Flow velocity

An example data of velocity measurement is shown in Fig. 3. The hot wire probe is positioned at *L* = 50 mm and *r* = 0 mm. This figure obviously shows that the velocity is highly fluctuating therefore the measured data are averaged for 180 seconds. The averaged velocities in each position are shown in Fig. 4 which is divided according to the distance *L*. Fig.4(a) includes the data of *L* = 50 mm to 400 mm while Fig. 4(b) includes *L* = 600 mm to 1200 mm. The data obtained at the position relatively nearer to the fan (Fig 4a) shows that the flow velocity and its gradient are generally large. For *r* = 0 to about 120 mm, the velocity becomes bigger with increasing *r*. Once *r* exceeds 120 mm which corresponds to outer edge of fan blade, the velocity drastically decreases and it reaches to zero at about *r* = 250 mm. The data trend at the position far from the fan (Fig .4b), is fairly different to that of nearer positions; the velocity becomes generally small and the velocity peak becomes unclearly observed.

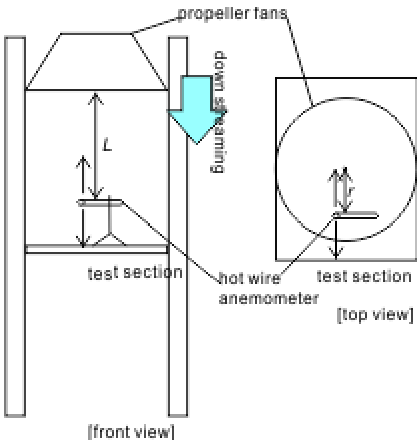


Fig. 1 Layout of test rig.

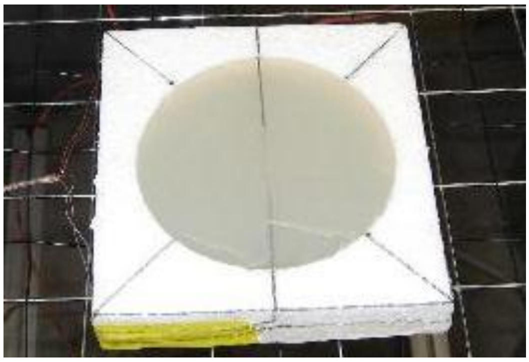


Fig. 2 Agarose gel with one dimension heat conduction

3.2. Heat transfer coefficient

Fig. 5 shows an example of time dependent temperature change at the center of brass sphere during cooling by the propeller fan. In order to derive heat transfer coefficient from this data, dimensionless temperature T_θ is applied by following definition shown as Eq. (1).

$$T_\theta = \frac{T_f - T_x}{T_f - T_i} \qquad (1)$$

The relationship of dimensionless temperature T_θ and time is presented by a straight line as clearly seen in Fig. 6. The equation of approximate straight line is obtained by least square method as shown in Figure 6. The inclination of this straight line is represented as G_{xi} which is determined by Eq. (2), thus the heat transfer coefficient h is derived from Eq. (2).

$$G_{xi} = -\frac{hA}{mc} \qquad (2)$$

In addition to measuring heat transfer coefficient of cooling by the propeller fan, the Eiffel air channel was used to measure heat transfer coefficient of cooling by the low turbulence air flow. Obtained values of heat transfer coefficient in each position are shown in Fig. 7. Fig.7 (a) includes the data of L = 50 mm to 400 mm while Fig. 7(b) includes L = 600 mm to 1200 mm. Fig. 7 and Fig. 4 show an almost similar characteristic. The data obtained at the position relatively nearer to the fan, shown in Fig. 7(a) suggests that the heat transfer coefficient and its gradient are generally large.

But different from Fig. 4, The position of peak shifted to r = 150 mm. For r = 0 to about 150 mm, the heat transfer coefficient becomes bigger with increasing r. Once the

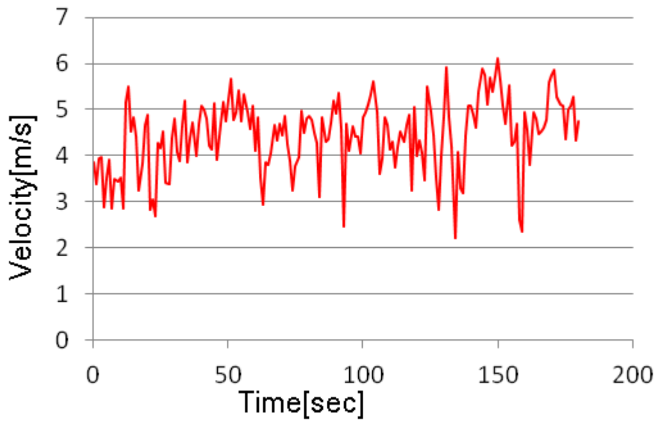
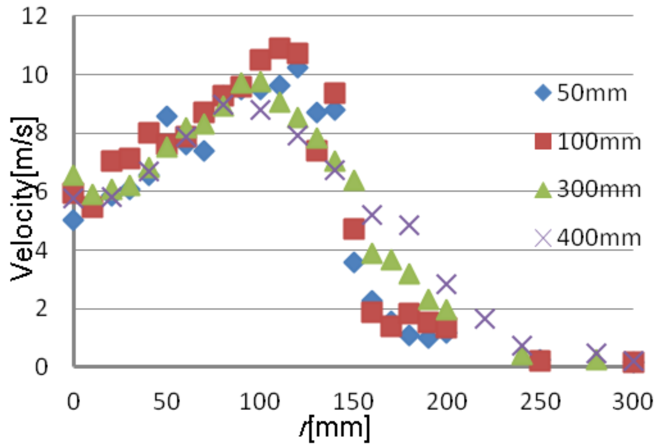
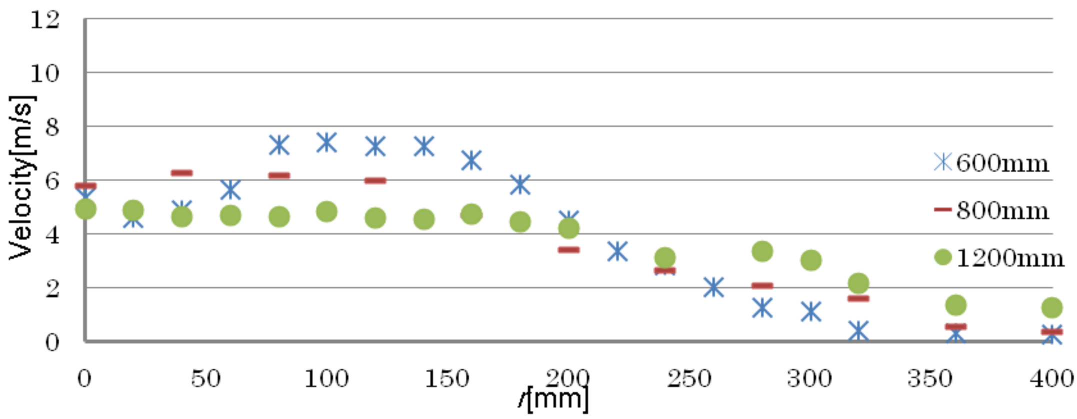


Fig. 3 An example of flow velocity from the propeller fan (L = 50 mm, r = 0 mm)



(a) L = 50 mm – 400 mm



(b) L = 600 mm – 1200 mm

Fig. 4 Flow velocity from the propeller fan r exceeds 150 mm which corresponds to outer edge of fan blade, the heat transfer coefficient gently decreases as shown in Fig. 7(a), nevertheless the velocity drastically decreases as shown in Fig. 4(a). Near the position of r = 150 mm, flow velocity doesn't correlate to the heat transfer coefficient, thus it can be inferred that heat transfer coefficient is not influenced by velocity.

Heat transfer coefficient and flow velocity measured at various positions in the air flow made by the propeller fan is plotted on Fig. 8. The continuous line in Fig. 8 represents the heat transfer coefficient obtained by the air flow made by Eiffel air channel that generate the low turbulence air flow. The figure clearly shows the heat transfer coefficient is larger in the flow made by the propeller fan than in the flow made by Eiffel air channel. Thus it can be considered propeller fans are effective to be used for cooling.

3.3. Turbulence intensity

We attempt to measure the turbulence intensity of the flow from the propeller fan to confirm the assumption that the air flow made by propeller fan has high turbulence intensity and realize heat transfer enhancement. Since the hot wire anemometer used in 3.1 is not sensitive to the rapid change of velocity, the fine hot wire anemometer is applied that can measure such fluctuating velocity as 5 kHz in its frequency. Measured velocity in the air flow from propeller fan at the position of L = 50 mm and r = 0 mm is shown in Fig. 9. Time-average velocity for 10 seconds is calculated and represented as U_a. And turbulence intensity was calculated as the root mean square of the deviation of velocity from the U_a divided by U_a, as shown in Eq. (3), (4).

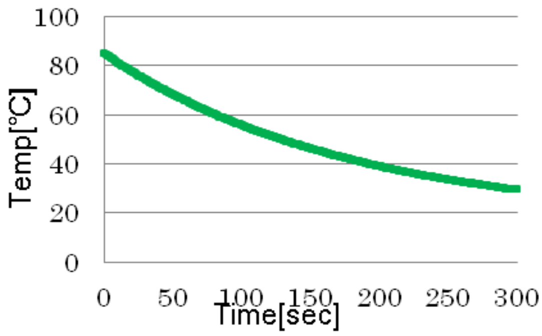


Fig. 5 An example of time dependent temperature change during cooling of brass sphere

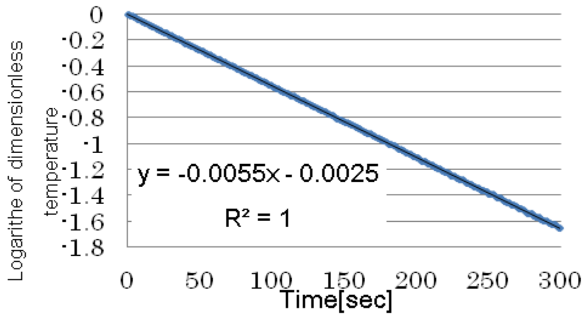
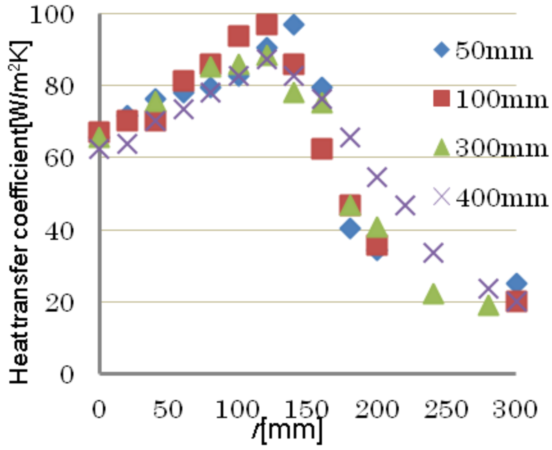
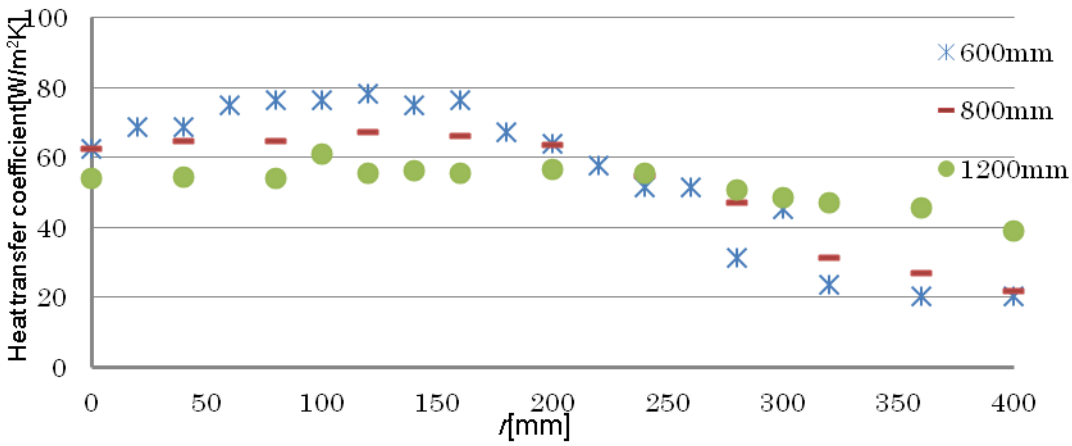


Fig. 6 Relationship between dimensionless temperature and time



(a) L = 50 mm - 400 mm



(b) L = 600 mm – 1200 mm

Fig. 7 Heat transfer coefficient of flow velocity from propeller fans

$$U_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(U_i - U_a)^2} \qquad (3)$$

$$T_i = \frac{U_{rms}}{U_a} \times 100 \qquad (4)$$

Distribution of turbulence intensity obtained at L = 50 mm is shown in Fig. 10. There is the peak near r = 150 mm. Taking into account the existing study by Torii *et al.* (1977) that reports higher turbulence intensity enhances heat transfer coefficient even with same flow velocity, the reason of the inconsistency observed at r = 150 mm that heat transfer coefficient was large even though flow velocity was small, as previously indicated in 3.3, would be the high turbulence intensity observed in Fig. 10.

3.4. Cooling of agarose gel

The conditions for experiments of cooling agarose gel was determined as four positions where the heat transfer coefficient was different with each other as specified by the symbol *A*, *B*, *C*, *D* in Fig. 8. In the current experiment, the positions corresponds to *A*, *B*, *C*, *D* are denoted as L = 100 mm and r = 240 mm, L = 1200 mm and r = 80 mm, L = 800 mm and r = 80 mm, L = 100 mm and r = 120 mm, respectively. Cylindrical agarose gel samples were placed as center of the circle coincided with the four positions denoted above. The obtained cooling curves are shown in Fig. 11. From the figures, it is confirmed that the agarose gel will be cooled more quickly if the sample is placed at the position with a larger heat transfer coefficient. Combined with the fact that the air flow from the propeller fan realizes a larger heat transfer coefficient than low turbulence flow, it is considered to be effective to apply propeller fans to actual food cooling process. It is also indicated that the temperature difference between center and surface in each sample becomes larger with increasing heat transfer coefficient. This is because the thermal conductivity is not so large in food materials, therefore the cooling rate in center of the sample becomes not so fast if the cooling rate in surface becomes much faster by enhanced heat transfer coefficient.

For further consideration about food cooling by propeller fans, a simple numerical calculation on one-dimensional heat transfer is made. Thermal property of water is used because the 97 % of agarose gel is occupied by water. As

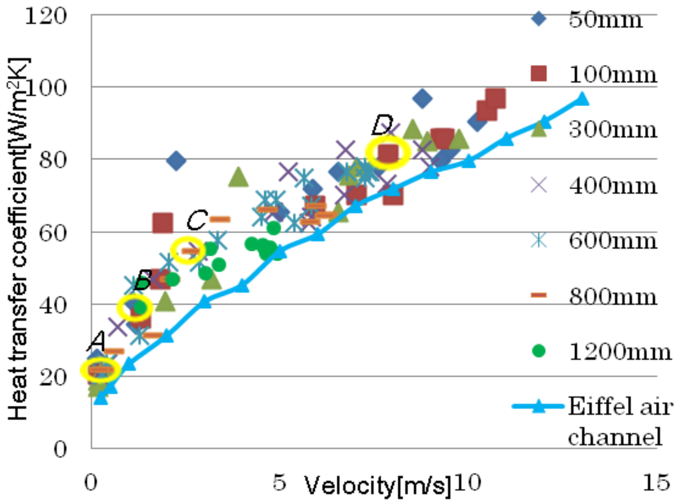


Fig. 8 Relationship between flow velocity and heat transfer coefficient obtained by propeller fan

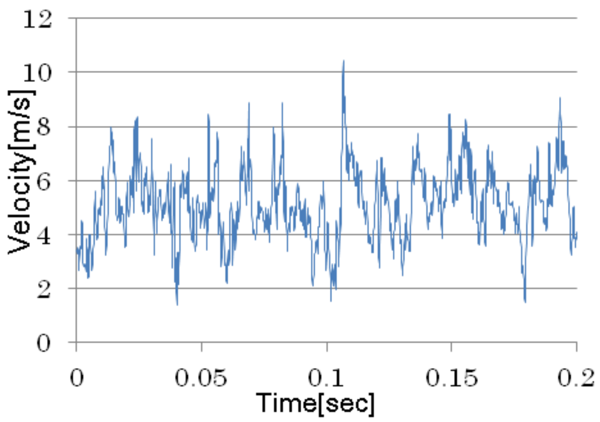


Fig. 9 An example of fine-hot wire anemometer measurement (L = 50 mm, r = 0 mm)

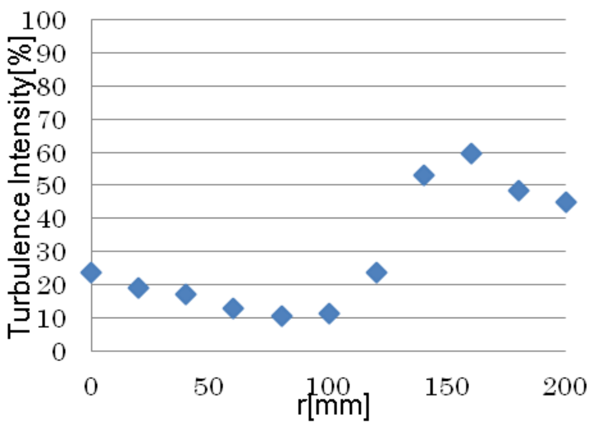


Fig. 10 Turbulence intensity measurement (L=50mm)

heat transfer coefficient, the value obtained at preliminary experiment made by using cylindrical copper block whose dimension is almost identical with agarose gel (ϕ80 mm x 17 mm) is adopted. The calculation result is shown in Fig. 12 but it is considerably different with the experimental data obtained at the same condition with the calculation (L = 800 mm, r = 80 mm, h = 59.7 W/m^{2}K), as shown in Fig. 11(c). It is clear that the cooling rate is faster in the experimental data. We considered this difference would be attributed to the water evaporation and resulted cooling by the latent heat of vaporization. Thus we attempted the cooling experiment with the surface of the sample wrapped with thin plastic film. The result is shown in Fig. 13 that is nearly identical to Fig. 12. It is confirmed to be important to take the water evaporation into account for cooling highly hydrated materials like food.

Since it is well known that there is analogy between heat transfer and mass transfer, if the turbulence enhance the heat transfer, mass transfer would also be promoted by turbulence. In this case, therefore, turbulence would promote the water vapor dispersion. In order to confirm the above assumption, we attempt the cooling experiment of agarose gel by using Eiffel air channel flow which has low turbulence and propeller fan which has high turbulence. The experimental condition is determined to realize the same heat transfer coefficient during cooling of cylindrical copper block by the Eiffel air channel and the propeller fan. The heat transfer coefficient was h = 54.2W/m^{2}K that was realized by the Eiffel air channel with 9.6m/s in flow velocity while that was realized by the propeller fan with 3.4m/s in the air velocity at the position of L = 100mm r = 170mm.Thus it is clear that the flow velocity by the propeller fan is smaller than Eiffel air channel even with same heat transfer coefficient that indicates highly turbulent flow can provide large heat transfer coefficient even the flow velocity is small.

The measured cooling curve is shown in Fig. 15 that clearly shows the lower cooling rate relative to Fig. 14. From the result, it is indicated that flow turbulence promote not only heat transfer coefficient but also water vapor dispersion and make the cooling rate much faster.

CONCLUSION

In order to investigate the effective application of propeller fans, several experiments were made and following results were obtained. Flow velocity by the propeller fan and its gradient are generally large at the position near the fan. The velocity is small at the center of the fan and becomes bigger with approaching to the edge of fan blade. With being out of the edge of fan blade, the velocity drastically decreases. But at the position far apart from the fan, the velocity becomes generally small and the velocity peak becomes not observed clearly.

Heat transfer coefficient and flow velocity show almost similar characteristic. But the peak position for heat transfer coefficient shifts to a little outer position of the edge of fan relative to the peak position for the velocity. And with being out of the edge of fan, the heat transfer coefficient gently decreases. The distribution of turbulence intensity obtained near the fan has a peak at the position almost identical with the peak position for heat transfer coefficient. Thus heat transfer coefficient is presumed to be enhanced not only by the velocity but by turbulence intensity.

It is confirmed that the heat transfer enhancement by propeller fan is also effective for highly hydrated materials like agarose gel. The highly turbulent flow is revealed to enhance not only heat transfer but water evaporation and accelerate the cooling.

From the above findings, it is suggested that the propeller fan has a potential for the effective cooling of food materials by utilizing its flow turbulence.

NOMENCLATURE

L	Distance from fan to probe	(mm)
r	Distance from center of fan	(mm)
U_i	Instantaneous flow velocity	(m/s)
U_a	Average flow velocity	(m/s)
U_{rms}	Flow velocity of root mean square value	(m/s)
T_i	Initial temperature	(°C)
T_x	Instantaneous temperature	(°C)
T_f	Ambient temperature	(°C)
T_θ	Dimensionless temperature	(°C)
T_s	Surface temperature	(°C)
T_c	Center temperature	(°C)
m	Weight	(kg)
c	Specific heat	(J/kgK)
A	Superficial eria	(m^2)
h	Heat transfer coefficient	(W/m^{2}K)
T_i	Turbulence intensity	(%)

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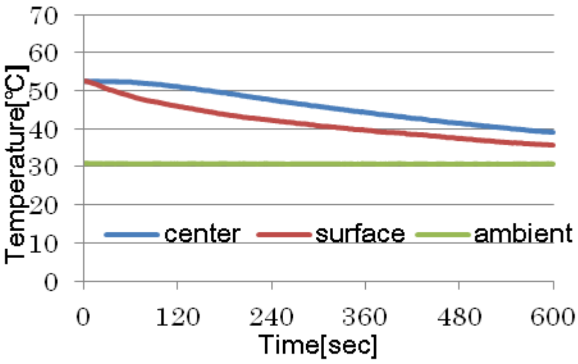
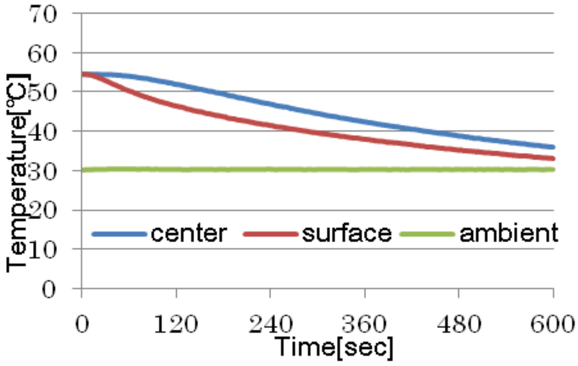
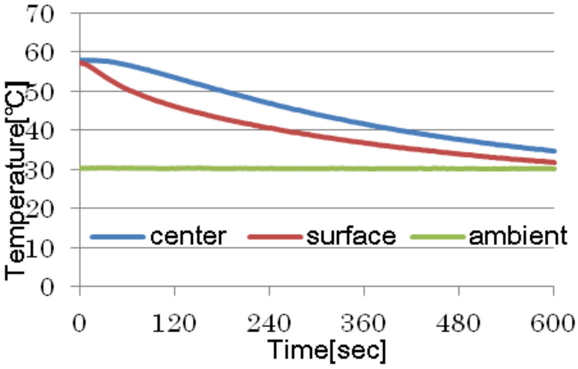


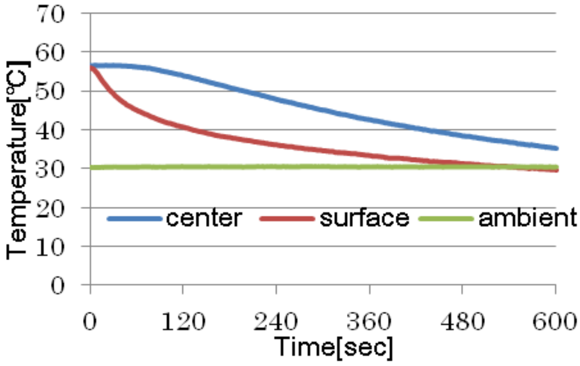
(a) A (L = 100 mm, r = 240 mm)



(b) B (L = 1200 mm, r = 80 mm)



(c) C (L = 800 mm, r = 80 mm)



(d) D (L = 100 mm, r = 120 mm)

Fig. 11 Cooling curves of agarose gel

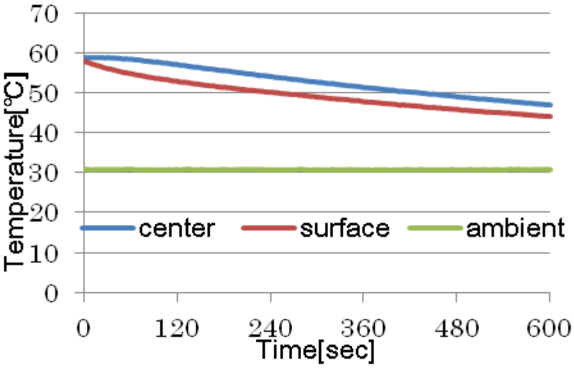


Fig. 12 Calculated cooling curves of agarose gel

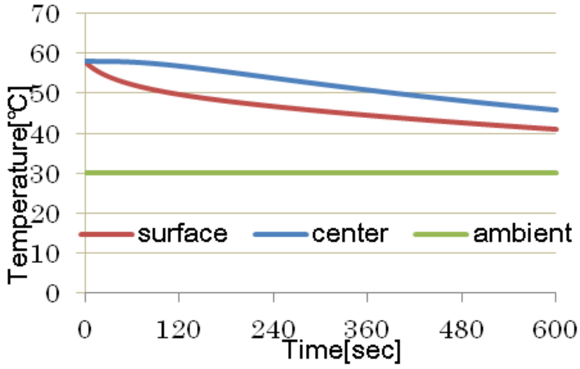


Fig. 13 Cooling curves of wrapped agarose gel

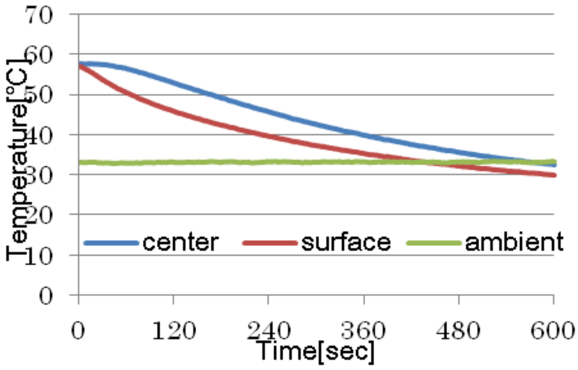


Fig. 14 Cooling curves by the propeller fan

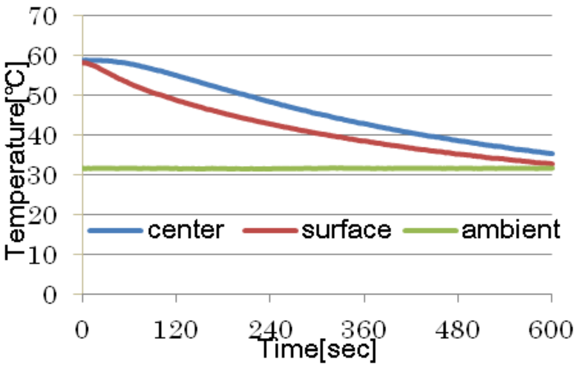


Fig. 15 Cooling curves by Eiffel air channel