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EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER IN PACKED BED OF VEGETABLES AND FRUITS

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ABSTRACT

Issues of the accurate measurement of heat transfer coefficient for packed bed of vegetables and fruit is complicated due to their complex geometry and the necessity to use fast as well as non-invasive method. The paper presents the basis of the innovative approach of the measurement of the average heat transfer coefficient by the use of the updated single blow method for the case of the packed bed of vegetables and fruits. The measurement approach was positively validated for the case of the packed bed of regular balls. The presented results cover heat transfer coefficient measured for carrot stored in packed beds for two various arrangements and apple stored under conditions of various turbulent intensity at the inlet to the bed from 2 up to 14%. The dimensionless heat transfer correlations were proposed on the basis of the obtained results. It was demonstrated that due to flow laminarisation inside the bed the turbulence intensity has no leading effect on heat transfer inside the bed. The influence of the bed arrangement on heat transfer is significant and heat transfer enhancement was demonstrated for the case of the irregular bed arrangement.

Keywords: heat transfer coefficient, refrigerated storage, packed bed, carrot, apple

1. INTRODUCTION

The paper presents an approach for the measurement of heat transfer and flow resistance in a packed vegetable bed for the exemplary case of carrots in two various arrangements in bed as well as packed fruit bed of apples. Knowledge of heat transfer conditions when cooling vegetables and fruits is necessary for the design of a refrigerated storage chamber.

The available in literature numerous heat transfer correlations relate mainly to the determination of heat transfer for beds consisted of the elements of simple and regular geometry, i.e. a flat plates, cylinders, cones or balls. The carrot beds discussed in this paper consist of the elements of complex geometry which means that the use of heat transfer correlations developed for the objects of simple geometry may lead to not acceptable prediction accuracy. The above difficulties are the motivations for the present research with use of the updated single blow method to determine heat transfer coefficient in the packed bed of vegetables or fruits.

2. METHOD OF SINGLE BLOW TECHNIQUE

The method used in the work to determine the average heat transfer coefficient in the vegetables and fruits bed, i.e. the single blow method, was successfully used, among others by Shaji and Das (2010), Krishnakumar et al. (2011), Butrymowicz et al. (2016), Ranganayakulu et al. (2017), for research on heat transfer in compact heat exchangers. The method was updated specifically in order to be applied for the case of a packed bed of fruits for the first time by Łapiński et al. (2017).

The heat transfer coefficient α is determined in the discussed method by comparison of the actual temperature profile of the air (heated at the inlet section to the tested bed) measured at the outlet section of the test bed with the predicted temperature profile determined on the basis of the theoretical model. During the measurement with the single blow method, air flows onto the tested bed as it is shown in Fig. 1.

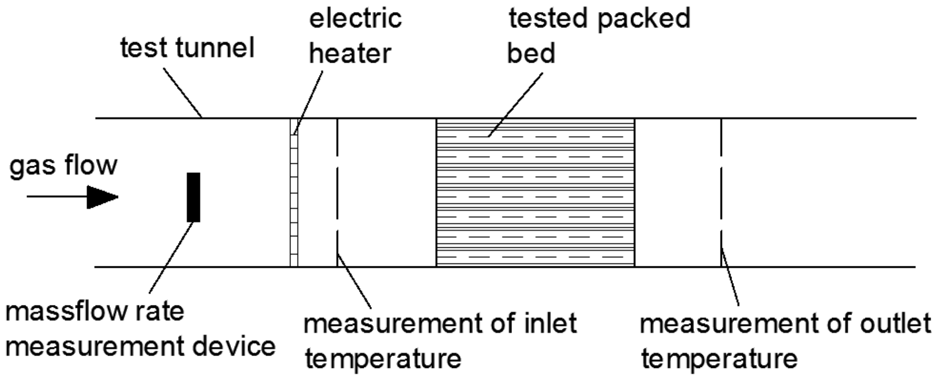


Figure 1: The schematic of the measurement approach by means of the single blow technique.

In the single blow method air at constant temperature is blown at the tested packed bed as it is shown in Fig. 1. The experimental tunnel walls are well insulated and flow developed inside the tunnel is fairly uniform due to application of the flow rectifier. Therefore, heat transfer at radial direction is eliminated and both flow as well as heat transfer may be treated as one-dimensional process. Air velocity, temperature, humidity, and turbulence intensity of air at the inlet to the tested bed is measured. The change in temperature of the flowing air at the inlet is caused by switching on the electric heater. As an effect of the temperature difference between air and tested packed bed the unsteady heat transfer occurs with resulting temperature changes at the bed outlet. The heat transfer coefficient α is determined by means of comparison of the actual air temperature profile measured at the outlet of the tested bed with the predicted temperature profile determined on the basis of the applied theoretical model. Heat transfer in the packed bed is modelled with use of porous body model.

The single blow method requires recording of air temperature profile directly at the inlet and the outlet of the tested bed. Air flow rate should be fixed during the measurement as well as it is required air temperature is constant and uniform in the radial direction at the inlet to the tested bed. Theoretical models of temperature profiles, used for comparison with the profile obtained from the experiment, are presented in the work of Butrymowicz et al. (2016). All the presented models are equivalent to each other, while the basic, one-dimensional model of heat transfer between a porous object and the fluid flowing through it was proposed by Anzelius (1926), which was also the basis for many further modifications.

One of the reasons for the possible inaccuracy in determination of heat transfer coefficient by the single blow method with use of the model of Anzelius (1926) is the difficulty in generation of the temperature jump at the inlet of the tested packed bed due to imperfect operation of the electric heater and additional thermal effects in the test tunnel at the inlet section. As a consequence, the predicted temperature profiles at the outlet of the tested bed do not accurately correspond to the measurement data. This requires to apply more accurate model that takes into account inlet temperature profile that may be identified experimentally. Model of convective heat transfer in porous body that takes into account the above effect was proposed by Liang and Yang (1975). These authors proposed an equation for a dimensionless temperature profile at the bed inlet as an exponential function as follows:

$$\theta_f(t,0) = 1 - e^{-t\tau^{*-1}} \tag{1}$$

Taking into account the above initial and appropriate boundary conditions, Liang and Yang (1975) obtained the following analytical solution for the unsteady temperature at the outlet of the porous body that may be formulated in the dimensionless form:

a) for $\tau < t^*$ (i.e.: $t < Lw_f^{-1}$), i.e. solution for time period in which the temperature jump did not reach the tested bed outlet:

$$\theta_f(\tau, NTU) = 0 \tag{2}$$

b) for $\tau \geq t^*$ (i.e. $t \geq Lw_f^{-1}$) the fluid temperature is:

$$\theta_f(\tau, NTU) = \frac{1}{\tau^*}\int_{\tau^*}^{\tau} e^{-(\tau-\eta)\tau^{*-1}-b_2 t^*}\left\{e^{-(\eta-t^*)}I_0\left(2\sqrt{b_2 t^*(\eta-t^*)}\right)+\int_0^{\eta-t^*} e^{-\xi}I_0\left(2\sqrt{b_2 t^* \xi}\right)d\xi\right\}d\eta \tag{3}$$

Details of the model were presented in the work of the authors Liang and Yang (1975) and in the works of Łapiński et al. (2017).

The above model was proved as useful and effective for the measurement of the average surface heat transfer coefficient for the packed bed for the case of heat exchanger matrices of rotating regenerative heat exchangers, Butrymowicz et al. (2016). The above model was preliminary verified for the case of the packed bed of vegetables, in the work Łapiński et al. (2017).

3. TEST APPARATURES

The experimental part of the single blow method in application to the measurement of the average effective heat transfer coefficient in a packed vegetable and fruit bed is carried out in a specially prepared test tunnel at the Bialystok University of Technology. The test stand was equipped with a measurement system that enables the measurement of the following parameters: temperature, pressure, air humidity, and air velocity. The schematic of the test tunnel is shown in Figure 2. The experimental stand was divided into four sections as it is shown in Figure 2, namely:

first section – flow intake, flow rectifier, and inlet conditions measurement section;

second section – the inlet to the test section fitted with the confusor;

third section – the measurement section with the tested packed bed and inlet and outlet thermocouples mesh structure;

fourth section – the outlet section fitted with the diffuser and the outflow fan.

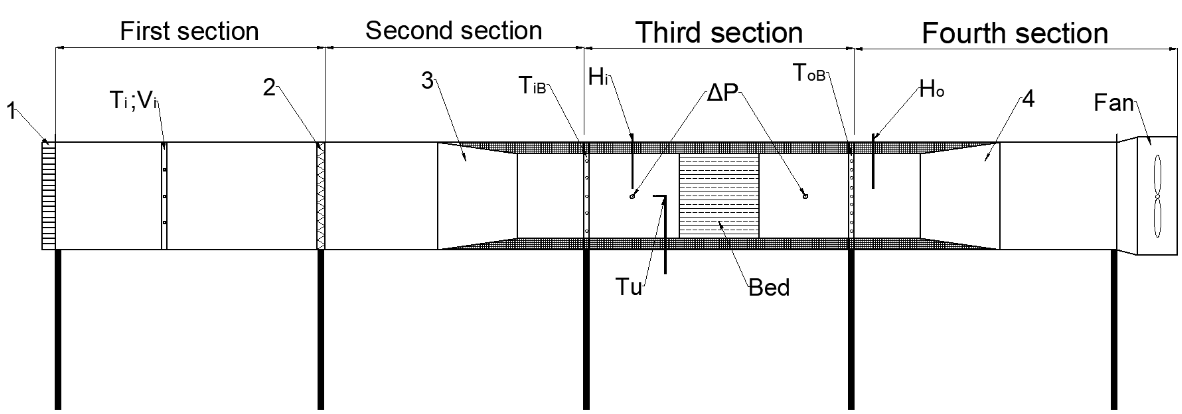


Figure 2: Schematic diagram of the test tunnel: 1 – flow rectifier; V_i – air flow rate meter; T_i temperature sensors; 2 - electric air heater; 3,4 – confusor/diffuser; T_{iB} – thermocouples mesh at the tested bed inlet; H_i,H_o – humidity sensors; ΔP – pressure gauges; Bed – tested packed bed; Tu – turbulence intensity probe; T_{oB} – thermocouples mesh at the tested bed outlet.

The measurements for the tested packed bed of carrot were made at two different vegetables arrangements: irregular (Figure 3a) and longitudinal (Figure 3b). Due to the shape of apples for this bed, the measurements were made for one arrangement (Figure 3c).

Figure 3: The tested packed beds:
a) carrot arrangement irregular, b) carrot arrangement longitudinal, c) apples.

The packed bed geometry was determined for each of the bed arrangement individually. In order to determine the accurate geometry of the tested bed the carrots and apples were divided into particular weight groups. The tested carrots have been classified by weight every 5 g, while tested apples were classified by weight every 10 g. Then in each weight group the piece of the average weight of the group was selected and the geometrical parameters were determined. For each selected element, the height and diameters along the element height were measured every 5 mm. Based on the measured lengths and diameters, 3D models were made in the SolidWorks program which allowed the determination of the actual surface of the tested vegetables and fruits. The averaged geometry of the tested carrots and apples is presented in Table 1.

Table 1: The averaged geometry of the tested carrots and apples

BED / Parameter	Carrots (irregular)	Carrots (longitudinal)	Apples
Average mass [kg]	33.87	35.69	16.496
Average heat transfer surface area [m^2]	4.934	5.179	1.806
Average volume [m^3]	0.0331	0.0349	0.0211
Average density [kg/dm^3]	1.023		0.784

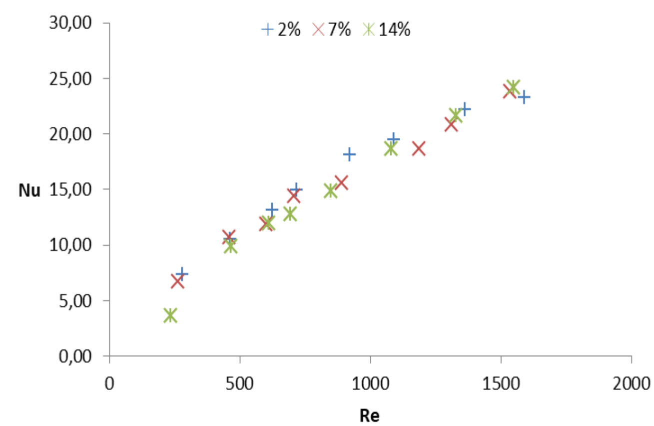
Figure 4: elements that disturb air flow inside the inlet section

As part of the measurements, the intensity of turbulence was measured in order to determine the effect of a given parameter on the heat transfer coefficient. The turbulence value was measured using a specialized turbulence probe from DANTEC Dynamics (StreamLine Pro anemometer). In order to change the level of turbulence intensity in the first section of the experimental section, the boxes were inserted as it is presented in Figure 4. As a result, the values of turbulence intensity were at the following levels: no boxes Tu = 2%; one box Tu = 7%; two boxes Tu = 14%.

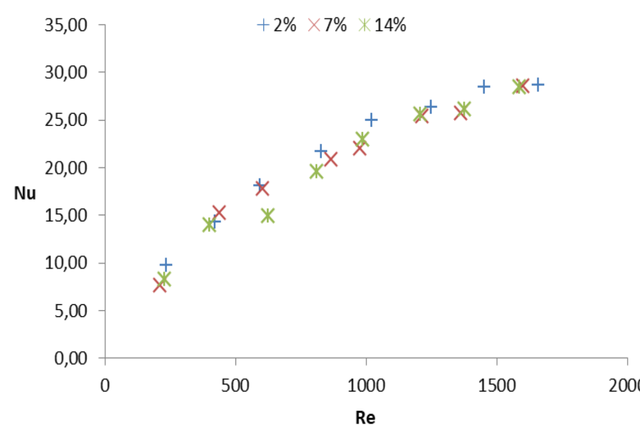
4. TEST RESULTS

The reported experimental investigations have been carried out for the packed beds consisted of carrot and apples. After processing the results obtained from the measurements using the geometry presented above, the results are presented graphically presented in Figure 5 and Figure 6. Figure 5 shows a comparison of the results of each bed, carrot and apple experiments at three different levels of the turbulence intensity Tu. In Figure 6, the authors present the effect of carrot bed arrangement on the Nusselt number Nu.

a)



b)



c)

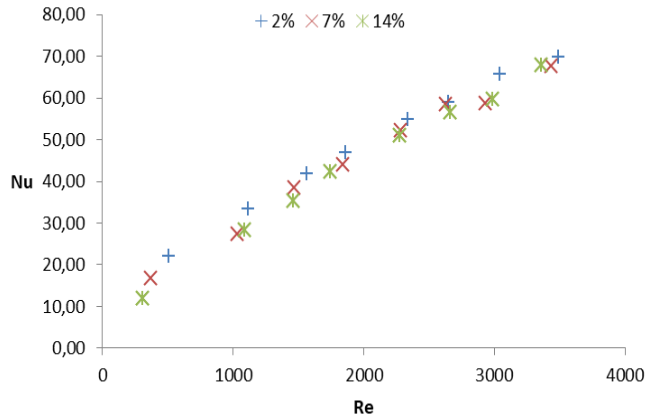


Figure 5: Comparison of results for three turbulence intensity levels:
a) carrots arrangement longitudinal, b) carrots arrangement irregular, c) apples.

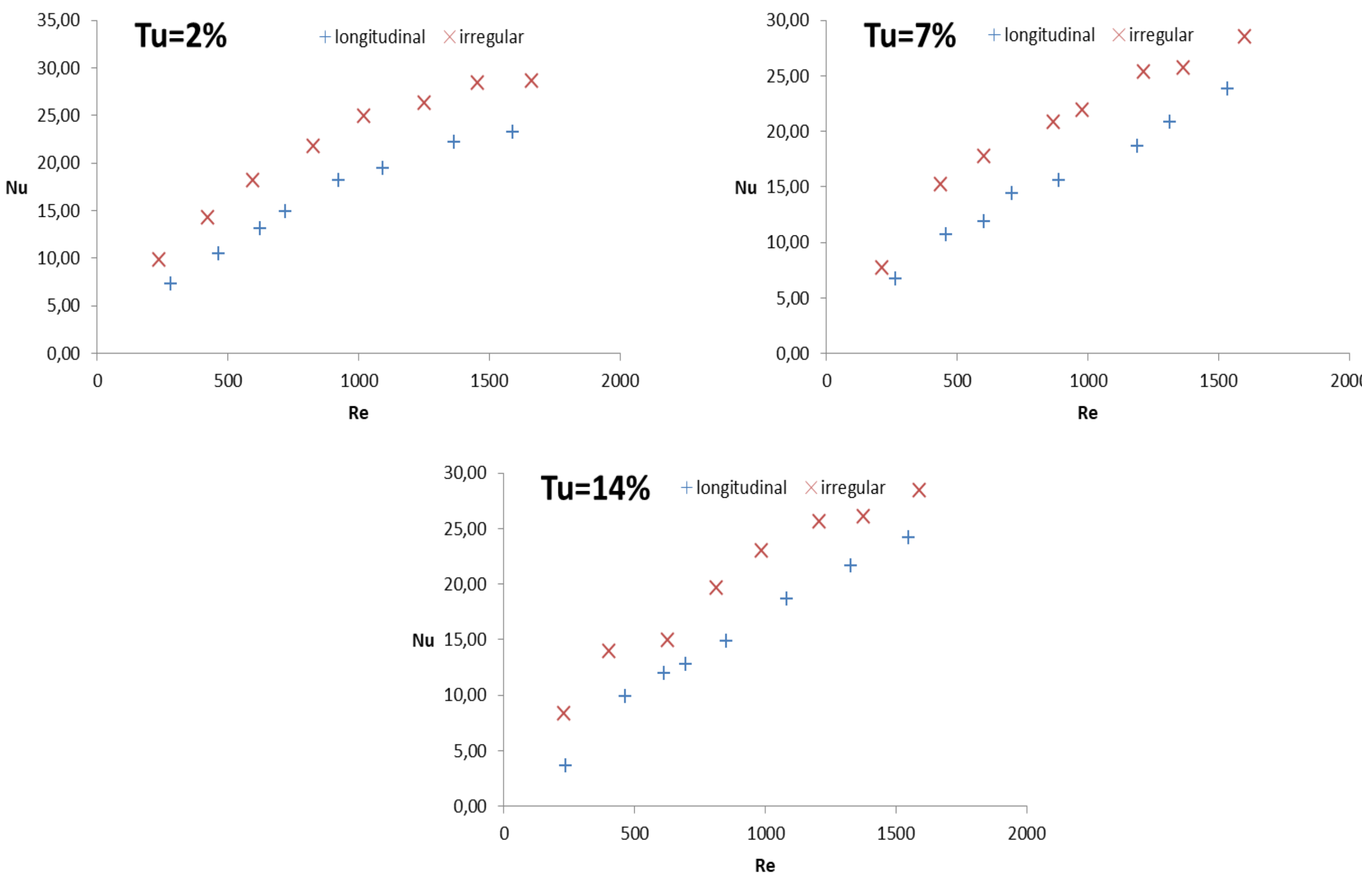


Figure 6: Comparison of results for the case of longitudinal and irregular carrots arrangement.

On the basis of the obtained results the generalised heat transfer dimensionless correlations using Reynolds number Re, Prandtl number Pr, which is determined relative to the measured temperature and humidity, and the intensity of turbulence Tu were proposed. The proposed relationships were developed separately for each the tested arrangements of the tested carrot and apples beds. For the case of the longitudinal carrots arrangement the following correlation may be proposed:

$$Nu = 0.0725\,\mathrm{Re}^{0,795}\,\mathrm{Pr}^{0,22}\,\mathrm{Tu}^{0,018} \tag{4}$$

For the above equation the determination coefficient is R^2= 0.971. The above relationship were made on the basis of experimental data obtained for the following range of the dimensionless numbers: 250 < Re < 1650; 0.02 < Tu < 0.14; 1.02 < Pr < 1.15. For the case of the irregular carrot arrangement the following correlation was proposed:

$$Nu = 0.377\,\mathrm{Re}^{0{,}591}\,\mathrm{Pr}^{0{,}25}\,\mathrm{Tu}^{0{,}012} \tag{5}$$

For the above equation the determination coefficient is R^2= 0.943. The above relationship were made on the basis of experimental data obtained for the following range of the dimensionless numbers: 200 < Re < 1700; 0.02 < Tu < 0.14; 1.02 < Pr < 1.26. For the case of the apples bed arrangement the following correlation was proposed:

$$Nu = 0.278\,\mathrm{Re}^{0{,}675}\,\mathrm{Pr}^{0{,}08}\,\mathrm{Tu}^{0{,}006} \tag{6}$$

For the above equation the determination coefficient is R^2= 0.984. The above relationship were made on the basis of experimental data obtained for the following range of the dimensionless numbers: 300 < Re < 3500; 0.02 < Tu < 0.14; 1.2 < Pr < 1.4.

The comparison of heat transfer results for various tested bed arrangements and at various intensities of turbulence allowed to analyse the influence of these parameters. As it is seen in Figure 5a, Figure 5b, and Figure 5c, in all tested cases of the tested packed beds the turbulence intensity does not produce significant effects on Nusselt number describing heat transfer. However, the exact exponent of Tu number was developed for the case of carrot bed. It is seen also that the effect of the bed arrangement is important for heat transfer process. This effect was possible for investigation just due to application of the proposed non invasive measurement approach, i.e. single blow technique. In the case of the irregular arrangement of carrots in the bed the heat transfer described by Nusselt number Nu is more intensive when compared to the longitudinal bed arrangement, see Figure 6.

5. CONCLUSIONS

The paper presents provides with the methodology for the measurement of the average effective heat transfer coefficient for the case of the packed vegetable and fruits bed. The results of the measurements for the case of carrot bed for two different bed arrangements and apples bed as well as three different intensity levels of turbulence of air were presented. The presented results allowed to draw the following general conclusions:

The effective application of the single blow method for the average heat transfer coefficient measurement for the packed bed of vegetables and fruits was demonstrated.

The intensity of turbulence produces slight effects on heat transfer irrespectively on the packed bed arrangement, i.e. whether the tested vegetables (carrot) is arranged longitudinally or irregularly, the same if we have a bed consisting of apples. This may be attributed to laminarisation of the air flow inside the bed: the range of Reynolds number at the inlet to the bed was Re = 1300 ÷ 11000 which indicates a transitional and turbulent flow while the range of Reynolds number inside the bed were Re = 200 ÷ 1700 which indicates laminar flow. The above range of Reynolds number may be thought as typical for practical applications in cold storage of the vegetables.

The influence of the bed arrangement on heat transfer is significant; the results show enhanced heat transfer for the case of the irregular arrangement carrot bed. This is the reason for the separate heat transfer correlations that were proposed for these two cases of the carrots packed bed.

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NOMENCLATURE

b_1	constant: $b_1 = b_2 \frac{v_f}{A_{f,\min}}$	b_2	constant: $b_2 = \frac{m_s c_s}{m_f c_f}$
A	heat transfer surface [m^2]	c	specific heat at constant prerssure [kJ/(kg·K)]
L	length of the tested packed bed section [m]	m	mass flow rate [kg/s]
NTU	Number of Heat transfer Units	Nu	Nusselt number
Re	Reynolds number	Pr	Prandtl number
T	temperature [°C]	t	time [s]
w_f	fluid velocity [m/s]	Tu	Intensity of turbulence
α	heat transfer coefficient [kW/(m^2·K)]	θ	dimessionless temperature
τ	dimenssionless time	η, ζ	dummy variables, dimensionless
τ_{sys}	time constant of solid-fluid system: $\tau_{sys} = \frac{m_s c_s}{\alpha A}$ [s]	τ^*	dimensionless time: $t^* = \frac{NTU}{b_1}$

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