Application of volumetric heat transfer coefficient on fluidized bed dryers

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Abstract – ***The input parameters of mathematical models are the heat transfer coefficient functions to describe the process of fluidized bed drying. Determining the contact surface of particles includes a number of uncertainties. The purpose of our work is to apply the volumetric heat transfer coefficient to create the criterial equations. During our work the results of the review of literature data are compared with our measurements.***

Keywords: fluidized bed dryer, heat- and mass transfer, criterial equation, volumetric heat transfer coefficient

I. Introduction

Fluidized bed dryers are widely used in the food and chemical industry to dry wet particles fast and effectively [1]. Some mathematical models are applied in the literature for describing the method of fluidized bed drying [2]. These models involves the solution of differential equation systems. The models are suitable to describe the temperature and moisture content distribution of the material and gas along the length of the dryer, and in the function of drying time. Furthermore, using these models the main parameters of the equipment can be specified without measurements. It is important to know the heat - and the mass transfer process during the drying and to apply sufficiently accurate thermal models describe the process to determine device parameters [3-4]. The input parameters of the mathematical models are the heat transfer coefficient equations beside the geometry and drying characteristics. The heat transfer coefficient equations are criterial equations, which can be determined by measurements. Modelling of fluidized bed dryers require the knowledge of heat transfer coefficient between gas and solid particles. Measuring the heat- and mass transfer surface of the fluidized material has a lot of difficulties. Determining the contact surface of particles includes a number of uncertainty due the irregular surface of particles, the size standard deviation, and the not ideal contact between gas and material. Using volumetric heat transfer coefficient and modified dimensionless numbers for the mathematical models are good possibilities describe the drying process of wet particles [5]. The purpose of our work is to apply the volumetric heat transfer coefficient for fluidized bed drying that eliminates the mentioned uncertainties in the heat transfer area. The results from the literature are compared with the results of our measurements.

II. Methods

A. Volumetric heat transfer coefficient

A pilot plant fluidized bed dryer device was developed to examine the phenomenon of fluidization, the simultaneous heat- and mass transfer during drying of particles and it makes possible to evaluate the volumetric heat transfer coefficient. We presented the device, the measuring method and the results during our prevouis works [6]. Some kind of grains were dried with varied operating parameters during our experiments.

Due the mentioned difficulities, a parameter can be given to characterise the contact surface, which depends on the geometry of the dryer, the properties of contact between gas and particles, and the hold-up of materials. This parameter is the volumetric interfacial surface area [7]:

$$a = \frac{A_{cont}}{V_{d,sta}} = \frac{A_{cont}}{A_d L_{sta}}, \quad (1)$$

where A_{cont} is the contact surface of materials, $V_{d,sta}$ is the volume of the dryer, where the particles staying, A_d is the surface of dryer, L_{sta} is the static height of particles. Fig. 1. shows the detail of the fluidized bed dryer presented the gas- and material flow, the main properties of gas and material, and the position of drying particles during the operation.

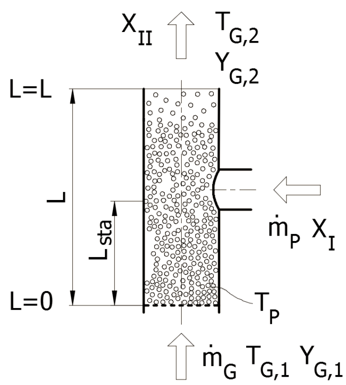


Figure 1. Sketch of the dryers section is showing the position of fluidized particles and the properties of material- and gas flow

The mass balance equation shows the connection between the amount of evaporated water from the material and the amount of humidity taken by the drying gas during the drying process:

$$\int_{t=0}^{t=t} \dot{m}_G (Y_{G,2} - Y_{G,1}) dt = \int_{X=X_I}^{X=X_{II}} m_{d,P} dX, \quad (2)$$

where $\dot{m}_G$ is the mass flow of drying gas, $Y_{G,1}$ is the absolute humidity of gas at the inlet point of dryer, $Y_{G,2}$ is the absolute humidity of gas at the outlet point of dryier, m_{dp} is the mass of dry particles, ΔX is the moisture content decrease of the material in time Δt. The heat balance equation shows the total heat flow between the particles and the drying gas. The total heat flow can be separated the heat flow for heating up the particles ($\dot{Q}_{heating}$) and the heat flow from evaporation ($\dot{Q}_{evap}$):

$$\dot{Q}_{total} = \dot{Q}_{heating} + \dot{Q}_{evap}. \tag{3}$$

At the constant drying rate period the heating up process is negligible, because the surface tempeature of materials is constant and it tends to the wet bulb temperature. The total heat flow using the mass balance equation (2):

$$\dot{Q}_{total} = \frac{m_{dP}\Delta X}{\Delta t} r_{H2O} = \dot{m}_G\left(Y_{G,2} - Y_{G,1}\right) r_{H2O}, \tag{4}$$

where r_{H2O} is the latent heat of evaporation. The convective heat flow according to Newton:

$$\dot{Q}_{total} = \alpha A_{cont}\left(\overline{T}_G - T_P\right), \tag{5}$$

where $\overline{T}_G$ is the average of inlet and outlet gas temperature, T_P is the temperature of the surface of particles. Combining Eqs. (4) and (5):

$$\alpha A_{cont}\left(\overline{T}_G - T_P\right) = \dot{m}_G\left(Y_{G,2} - Y_{G,1}\right) r_{H2O}. \tag{6}$$

The volumetric heat transfer coefficient obtained from Eqs. (1) and (6) in the constant drying rate period:

$$\alpha a = \frac{\dot{m}_G\left(Y_{G,2} - Y_{G,1}\right) r_{H2O}}{\left(\overline{T}_G - T_P\right) A_d L_{sta}}. \tag{7}$$

The main advantage of using the volumetric heat coefficient is, that the correlation (7) contains easily calculable parameters with less uncertainties. It means, that calculating this value the real shape and the amount of the particles in the dryer, and the properties of gas-material contact, so the surface area of the particles is unconserned.

The Reynolds- and the modified Nusselt-numbers are the components of the criterial equations for modelling fluidized bed drying:

$$Re = \frac{v_G \cdot d_p}{\nu_G} \qquad Nu' = \frac{\alpha a \cdot d_p^{\,2}}{\lambda_G}. \tag{8}$$

B. Summary of the dimensionless equations from the literature

In the literature there are several *Nu=f(Re)* equations using to characterize the heat transfer between solids and drying gas. Equations from literature were summerised in Table 1, which are valid in the case of fluidized bed drying. The plots of the listed *Nu=f(Re)* equations from the literature are represented in Fig. 2. The general ascertainment of these studies is, that the basis of the dimensionless equations is the heat transfer coefficient between gas and material.

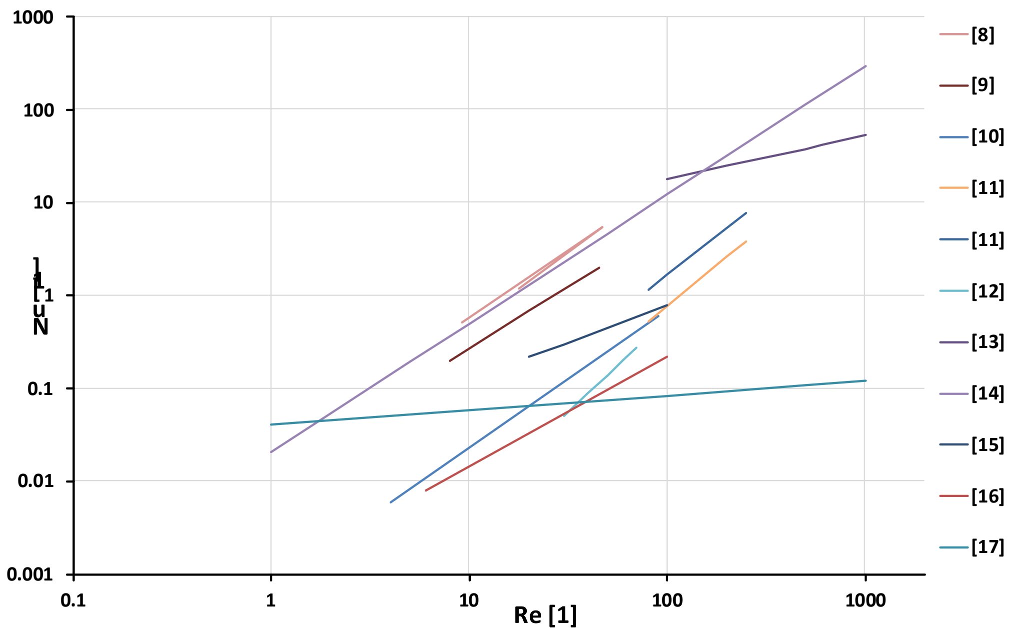
The heat transfer coefficient can be calculated with making some approximations, like to assume that the geometry of particles is sphere, and the contact between gas and material is ideal. These mean, that during the drying each particle are in contact with the drying gas, on its whole surface. With these assumptions, knowing the total number of particles in the drying chamber, the contact surface of material can be determined (6).

It can be stated, that these equations differ significantly each other due the inaccuracy of determining the contact surface. We revised the measurements results of literature data available, and evaluated the volumetric heat transfer coefficient from them.

C. Review of literature data

During our work we revised the measurements data from some literature sources. The calculations can be applied only those studies, where the dimensionless equations with their scopes were published, and the measurement conditions and the specifications of the particles were published as well. Other important condition was during the review, that the studies dealt with the case of drying, and the criterial equations are valid on the constant drying rate period. Usually there were lack of measured data available, so the heat transfer coefficient was calculated using iteration. During the

Ref.	Equations	Scope
Heertjes [8]	$\alpha = 7.427Re^{0.78}$	$8.8 < Re < 52.3$
Kettelring [9]	$Nu = 0.0135Re^{1.3}$	$9 < Re < 55$
Kumaresan [10]	$5.6493 \cdot 10^{-6}Re^{1.997}$	$30 < Re < 70$ and $0.0106 < Nu < 0.298$
Alvarez [11]	$Nu = 2.41 \cdot 10^{-4}Re^{1.752}$	$80 < Re < 250$
Alvarez [11]	$Nu = 8.24 \cdot 10^{-4}Re^{1.655}$	$80 < Re < 250$
Ciesielczyk [12]	$Nu = 0.106Re \cdot Ar^{0.0427}\left(\frac{L}{d_p}\right)^{-0.802}\varphi^{1.32}$	$3.61 < Re < 125.9$ and $1.24 \cdot 10^{3} < Ar < 1.14 \cdot 10^{5}$ $121 < \frac{L}{d_o} < 705$ and $1.14 < \varphi < 1.81$
Ranz [13]	$Nu = 2 + 1.8Re^{0.5}Pr^{0.33}$	$100 < Re$
Roy [14]	$Nu = 0.0205Re^{1.3876}Pr^{0.33}$	$1 \leq Re \leq 10^{3}$
Fedorov [15]	$Nu = 1.63 \cdot 10^{-3}Ar^{0.148}Re^{0.65}\left(\frac{L}{d_p}\right)^{-0.14}$	$2 \cdot 10^{3} < Ar < 7{,}5 \cdot 10^{5}$ $20 < Re < 100$
Shi-Jan-Fou [16]	$Nu = 0.25Re\left(\frac{L_{mcd}}{d_p}\right)^{0.2}$	$5.5 < Re < 280$ and $7.85 < \frac{L}{d_o} < 130$
Khorshidi [17]	$Nu = 0.0411Re^{0.155}$	$1 < Re < 1000$



review the heat transfer coefficient and the volumetric heat transfer coefficient were evaluated.

Knowing the $Nu=f(Re)$ equations, and its scopes, the heat transfer coefficient can be calculated with iteration. The iteration steps are the following:

1st step: The Reynolds-number was calculated from the measured data. The absent data were set up to an optional value.

2nd step: The value Nu_{crit} was evaluated from the criterial equation with using the Reynolds-number.

3rd step: The heat transfer coefficient was calculated (6) from the given, or adjusted parameters.

4th step: Calculating $Nu_{calc} = \dfrac{\alpha \cdot d_P}{\lambda_G}$.

The method iteration is complete, when the deviation between Nu_{calc} and Nu_{crit} is less than 1% $\left|\dfrac{Nu_{crit} - Nu_{calc}}{Nu_{calc}}\right| < 0.01$.

After the iteration of heat transfer coefficient every important operation parameters are known. Using Eq. (7) the volumetric heat transfer coefficient can be calculated, than the modified Nusselt-number (8) can be evaluated.

Kumaresan et al. [10] carried on experiments in the constant drying rate period on a fluidized bed dryer in batch operation. The diameter of the experimental apparatus was *55 mm*, the height was *435 mm.* The particles used for the experiments were ammonium-chloride with particle diameter between *0.495 ÷ 0.912 mm*, the velocity of inlet air *1.136 ÷ 1.391 m/s*, the range of its temperature *60 ÷ 75 °C*, the initial moisture content $0.04 \div 0.06\ kg_{H2O}/kg_{dP}$, and the mass of the fluidized particles varied in the range *0.09 ÷ 0.13 kg*. The equation for determining the heat transfer coefficient is:

$$Nu_{Kumaresan} = 5.649 \cdot 10^{-6} Re^{1.997}, \quad (9)$$

Eq. (9) is valid $30 < Re < 70$ and $0.0106 < Nu < 0.298$.

Alvarez et al. [11] used two different types of materials for their pilot-plant fluidized bed drying experiments: soya meal, sawdust and fish meal. The velocity of drying gas ranged between *2.8 ÷ 3 m/s*, the inlet temperature was *65 ÷ 105 °C.* The dimensionless correlation using the measurement data of soya meal:

$$Nu_{soya\ meal,Alvarez} = 2.41 \cdot 10^{-4} Re^{1.753}, \quad (10)$$

$$Nu_{sawdust,Alvarez} = 8.24 \cdot 10^{-4} Re^{1.655}, \quad (11)$$

Eq. (10) and (11) are valid on $80 < Re < 250$.

Ciesielczyk et al. [12] used in their experiments Polytetrafluoro-ethylene, ammonium sulphate, sand and silica gel. 208 measurements were performed, from these 97 measurements are suitable to study the falling drying rate period as well. Particle sizes ranged from *0.339 ÷ 1.24 mm,* the inlet temperature *333 K* and *363 K,* static bed height between *150 mm* and *240 mm,* air velocity from *0.2 ÷ 1.8 m/s.* The initial moisture content of materials was constant in every measurements. The criterial equation for Nu-Re correlation is:

$$Nu_{Ciesielczyk} = 0.106 Re\, Ar^{0.0437} \left(\frac{L_{sta}}{d_{1P}}\right) \Phi^{1.12}, \quad (12)$$

Eq. (12) is valid: $3.61 < Re < 125.9$ and $1.24 \cdot 10^3 < Ar < 1.14 \cdot 10^5$ and $121 < \frac{L}{d_P} < 705$ and $1.14 < \Phi < 1.81$.

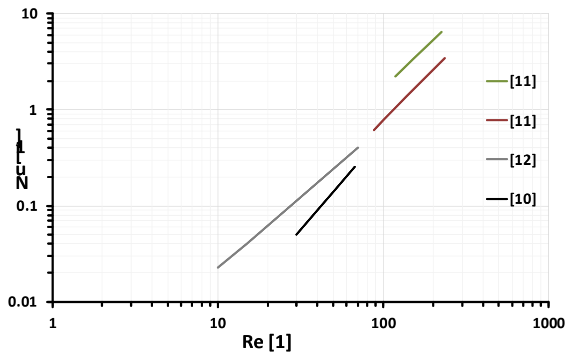


Figure 3. Comparison of dimensionless equations from [10-12]

III. Results

Fig. 3. shows the mentioned *Nu=f(Re)* dimensionless equations (9)-(12) from the literature with their scopes [10-12], where the measurement conditions were known. There are many other *Nu=f(Re)* functions located in the literature, but the calculations could be done only on the mentioned publications due the lack of the measurement data.

Fig. 4. shows the converted measurement points from literature with our results evaluated from the measurements. The revised data using modified Nu'-Re equations show better fit compared to the original values. The results show proper conformity with data based on literature and the results of our measurements.

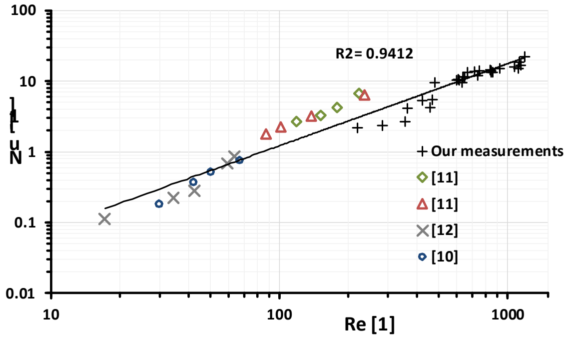


Figure 4. *Nu' vs Re* correlation of literature cited and our measurements [10-12]

A trendline was fitted to the measurement points, which shows strong correlation. The coefficient of determination to the measurements points is $R^2 = 0.9412$. Using volumetric heat transfer coefficient and modified Nusselt-number the margin of error can be reduced.

IV. Conclusion

The purpose of our work is to introduce the volumetric heat transfer coefficient for fluidized bed drying, which eliminates the uncertainties the determination of the heat transfer surface between gas and particles. Modified *Nu'=f(Re)* equation shows proper correlation between the results of the measurements in the literature, and the results of our measurements. The goal of our work is a new method for scaling up fluidized bed dryers using volumetric heat transfer coefficient.

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References

[1] A. S. Mujumdar, „Heat Transfer in Fluidized Beds – An Overview," *Special Topic in ME6204 Convective Heat Transfer, ME Department,* NUS, 2010.

[2] J. S. Walton, R. L.Olson, and O. Levenspiel, "Gas-Solid Film Coefficients of Heat Transfer in Fluidized Coal Beds," *Ind. Chem. Eng.* vol. 44, pp. 1474-1480, 1952.

[3] M. Kassai and C. J. Simonson, "Performance investigation of liquid-to-air membrane energy exchanger under low solution/air heat capacity rates ratio conditions," *Building Services Engineering Research & Technology*. vol. 36. n. 5. pp. 535-545, 2015.

[4] M. Kassai, G. Ge and C. J. Simonson, "Dehumidification performance investigation of liquid-to-air membrane energy exchanger system," *Thermal Science*. DOI: 10.2298/TSCI140816129K (*Accapted article*), 2014.

[5] T. Poós and M. Örvös, "Heat- and mass transfer in agitated co- or countercurrent, conductive-convective heated drum dryer," *Drying Technology*, vol. 30. n. 13. pp. 1457-1468, 2012.

[6] M. Örvös, V. Szabó and T. Poós, "Volumetric heat transfer coefficient for modelling the fluidized bed dryers," *5th European Drying Conference*, ISBN: 978-963-9970-62-5, pp. 296-303, 2015.

[7] R. E. Treybal, *Mass-transfer operations,* 3rd edition, McGraw-Hill Company, New York, 1981.

[8] P. M. Heertjes and S. W. McKibbins, "The partial coefficient of heat transfer in a drying fluidized bed", *Chem. Eng Sci.* vol. 5, pp. 161-167, 1956.

[9] K. N. Kettelring, E. L. Manderfield and J. M. Smith, "Heat and Mass Transfer in Fluidized System", *Chem. Eng. Progr.* vol. 46, pp. 139, 1950.

[10] R. Kumaresan and T. Viruthagiri, "Simultaneous heat and mass transfer studies in drying ammonium chloride in a batch-fluidized bed dryer," *Indian Journal of Chemical Technology*, vol. 13. n. 5. pp. 440-447, 2006.

[11] P. Alverez and C. Shene, "Experimental study of the heat and mass transfer during drying in a fluidized bed dryer," Drying Technology, vol. 14. n. 3-4. pp. 701-718, 1996.

[12] W. Ciesielczyk and M. Mrowiec, "The method of decreasing the number of experiments needed to design a fluidized bed drying," *Inz. Chem. I Proc.,* vol. 4. n. 12. pp. 551-567. 1991.

[13] W. E. Ranz and W. R. Marshall, "Evaporation of drops," *Chem. Eng. Progr.* vol. 48. n. 3. pp. 141-146, 1952.

[14] P. Roy, M. Vashishtha, R. Khanna and D. Subbarao, "Heat and mass transfer study in fluidized bed granulation—Prediction of entry length", *Particuology*, vol. 7. n. 3. pp. 215-219, 2009.

[15] J. M. Fiedorov, "Teorija I rascziot prociessa suszki wo wzwiesziennom stoje," *Goseniergaizdat*, Minsk, 1976.

[16] S. Jan-Fou, P. G. Romankow, and P. G. Raszkowska, *Zurnal. Prikl. Chimii,* vol. 3, pp. 530, 1962.

[17] J. Khorshidi, H. Davari and F. Dehbozorgi, "Model Making for Heat Transfer in a Fluidized Bed Dryer", *Journal of Basic and Applied Scientific Research*, vol. 1, n. 10, pp. 1732-1738, 2011.

[18] J. Nyers, L. Garbai, A. Nyers: A modified mathematical model of heat pump's condenser for analytical optimization. International J. Energy. Vol. 80, pp. 706-714, 2015. (IF 4.844)