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Thermal conductance of pneumatic conveying preheater for air–gypsum and air–sand heat transfer

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ABSTRACT

The use of pneumatic conveying duct as gas–solid heat exchanger is in vogue in the form of preheater and dryer in cement and pharmaceutical industries, among several other industries. Experiments were conducted to study the effect of solids feed rate, particle size and air velocity on thermal conductance of a vertical pneumatic conveying heat exchanger for preheating of dry solids. Sand and gypsum were used as cold medium while air was used as hot medium. Thermal conductance (defined as the ratio of heat transfer rate to driving force) was found to increase with solids feed rate and air velocity. A dimensionless correlation has been proposed for thermal conductance that predicts the present experimental data for air–sand and air–gypsum heat transfer within an error of ±18%. The relevant properties of solids are incorporated in the form of a dimensionless number, Fedorov number (Fe). The proposed correlation may be used to analyze pneumatic conveying heat exchanger of similar geometry.

1. Introduction

Gas–solid heat transfer finds immense applications in cement, mineral, power and pharmaceutical industries. Packed beds, fluidized beds and pneumatic conveying ducts can be used to achieve heat transfer between gas and solid phases. Gas–solid heat transfer in packed beds and fluidized beds has been widely studied and reviewed [1–4]. Bandrowski and Kaczmarzyk [5] reported air–ceramic spheres heat transfer in a vertical pneumatic conveying duct and studied the effect of air velocity and particle size on gas–particle heat transfer coefficient. Rajan et al. [6] presented a brief review of work carried out on gas–solid heat transfer in pneumatic conveying dryers and heat exchangers. In our earlier works [6,7], air–gypsum heat transfer was investigated in the vertical pneumatic conveying heat exchanger and results were presented in terms of thermal effectiveness and heat transfer coefficient. The present study is an extension of our earlier work with experiments carried out additionally using sand in the pneumatic conveying heat exchanger described in our earlier works [6,7].

Heat transfer coefficient is a widely used parameter in the analysis of heat exchangers, the use of which requires knowledge of heat transfer area. Unlike conventional heat exchangers where heat transfer area is fixed from the dimensions of the heat exchanger, heat transfer area in a pneumatic conveying heat exchanger is assumed to be the total external surface area of all particles in the duct [7]. Determination of heat transfer area requires knowledge of solids holdup or solid volume concentration, which are difficult to measure in industrial pneumatic conveying preheater units. Solid volume concentration may be estimated for the fully developed gas–solid flow by equating the pressure gradient to weight of solids in the duct. However, it has also been highlighted that the pressure gradient method to determine solid volume concentration may produce erroneous results in dilute flows and in small diameter pipes due to friction [8].

To circumvent problems associated with the determination of solid volume concentration and heat transfer area, thermal conductance (the product of heat transfer coefficient and heat transfer area) can be used in the design and analysis of pneumatic conveying heat exchanger. Thermal conductance has been used to study the effect of addition of hot particles on heat transfer between hot gas and cold particles in a vertical gas–solid pneumatic transport system [9]. Hence, in the present study results are presented in terms of thermal conductance of heat exchanger operating at low gas velocities involving air–gypsum (calculated from our earlier work) and air–sand heat transfer (from the experiments carried out in the present study). An empirical correlation for the prediction of thermal conductance of heat exchanger for air–sand and air–gypsum has been developed using dimensionless numbers requiring gas and particle properties and easily measurable bulk flow parameters. This approach may

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Nomenclature

English symbols

Term	Definition
(h_pA_h/k_gL)	Dimensionless thermal conductance (–)
A_h	Heat transfer area (m^2)
b_0	Constant in Eq. (11) (–)
b_1, b_2, b_3, b_4	Exponents in Eq. (11) (–)
C_p	Specific heat of air ($J\,kg^{-1}\,K^{-1}$)
C_{ps}	Specific heat of solids ($J\,kg^{-1}\,K^{-1}$)
D	Diameter of the duct (m)
D_p	Particle diameter (m)
Fe	Fedorov number (–)
Fm	Solid loading ratio (–)
g	Acceleration due to gravity ($m\,s^{-2}$)
h_p	Gas–particle heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_pA_h	Thermal conductance of heat exchanger ($W\,K^{-1}$)
k_a	Thermal conductivity of air ($W\,m^{-1}\,K^{-1}$)
ΔT	Log-mean temperature difference (K)
m_g	Mass flow rate of gas or air ($kg\,s^{-1}$)
m_s	Mass flow rate or feed rate of solid ($kg\,s^{-1}$)
Q	Air–solid heat transfer rate (W)
Re_p	Particle Reynolds number (–)
T_{g1}	Exit air temperature in single-phase flow (°C)
T_{g2}	Exit air temperature in two-phase flow (°C)
T_{gin}	Temperature of air entering the solid feeding section (°C)
T_{s1}	Temperature of solids feed (°C)
T_{s2}	Temperature of solids at the top of the duct (°C)
v_a	Average velocity of air in the duct (m/s)

Greek symbols

Term	Definition
μ_a	Viscosity of air (kg/ms)
ρ_a	Density of air (kg/m^3)
ρ_s	Density of solid (kg/m^3)
σ	Volumetric specific heat ratio (–)

facilitate analysis of industrial pneumatic conveying heat exchanger system.

2. Hydrodynamics of dilute phase pneumatic conveying

Understanding hydrodynamics of pneumatic conveying is essential for development of any application involving pneumatic conveying. Hydrodynamics of pneumatic conveying has been well studied and established as evident from literature [10,11]. Dilute phase conveying is characterized by high gas velocities (several times greater than the particle terminal velocity), very low solid volume concentrations and low pressure drop [12]. Particles are assumed to be suspended in the gas stream in dilute phase conveying and hence normally all particle–particle contacts are neglected. Solid loading ratio (ratio of solid to gas mass flow rates) is one of the parameters widely used to distinguish between dilute phase and dense phase pneumatic conveying where high solid concentrations and particle–particle collisions prevail.

In vertical pneumatic conveying, particles are accelerated from an initially low velocity to a larger velocity due to momentum transfer from gas through drag. Higher drag force leads to increased particle velocities. Drag force in pneumatic conveying increases with decrease in particle size and increase in solid volume concentration and slip velocity [13]. Slip velocity is the difference between gas and particle velocities. Small particles experience higher drag due to higher drag coefficient and smaller size and hence are rapidly accelerated in comparison with large particles leading to their lower concentration in the duct. Subsequently at a constant air velocity and solids feed rate, solid volume concentration increases with particle size.

With increase in gas velocity at a constant solids feed rate and particle size, solid volume concentration decreases owing to higher drag caused by higher slip velocity. In pneumatic conveying, at a constant air velocity for a fixed particle size, with increase in solids feed rate the number of solid particles in the duct is more, leading to increased solid concentration.

In the lower portions of the pneumatic conveying duct, slip velocity is high owing to higher gas velocity and lower solid velocity. Solid volume concentration, a ratio of solids mass flux to the product of particle density and solids velocity is high at the duct bottom due to lower solid velocity. Moving along the duct height, solid velocity increases and hence solid volume concentration decreases. Also the slip velocity decreases with duct height at a faster rate in the lower portions of the duct compared to that in the upper portions. This leads to varying solid concentrations at different axial locations in the duct. Axial solid volume concentration gradient in the pneumatic conveying duct is a function of particle size, solids feed rate, air flow rate and duct dimensions and may be qualitatively predicted using well established models reported in the literature [14].

3. Experimental

The experimental setup used in the study is described in our earlier works [6,7]. In a nutshell, the pneumatic conveying test rig is made of galvanized iron of 54 mm inner diameter and 2.2 m high, with thermocouple ports at five axial locations along the duct. The inlet temperature of gas is measured close to the solids feeder and the outlet temperature is measured using the temperature sensor located at the exit of the vertical duct (at the location of 2.2 m from the bottom). The range of variables investigated is given in Table 1. The range of variables have been chosen to collect experiment data with particle sizes smaller than 800 μm (minimum particle size reported in [5] is 700 μm) and air velocity lower than 10 m/s since other investigators have tested at gas velocities typically greater than 10 m/s. Since the present work deals with preheating of dry solids using hot air, the moisture content in the solids is assumed to be negligible.

4. Results and discussions

4.1. Estimation of air–solid heat transfer rate

It is widely acknowledged that there exist considerable difficulties in measuring particle temperature in gas–solid flows [15]. Hence, Rajan et al. [6,7] determined the air–solid heat transfer from the difference in steady-state temperature of air at the top of the duct (at the axial location of 2.2 m from bottom) in the single-phase

Table 1
Range of variables investigated.

S. No	Variable	Value
1	Particle size	231, 303, 390, 460, 547.5 and 722.5 μm
2	Air velocity	4.21–5.81 m/s
3	Solids feed rate	1.0–14.1 g/s

flow and in air–solid flow, thereby circumventing the necessity to measure exit temperature of solids. This method of determination of gas–solid heat transfer rate takes in to account of the heat losses in the duct as well. Hence,

$$Q = m_g C_p (T_{g1} - T_{g2}) \tag{1}$$

where T_{g1} and T_{g2} are steady-state temperatures of air at the top of the duct (at the axial location of 2.2 m from bottom) in single-phase and two-phase flow. This difference in temperature of air is due to the heat transfer from hot air to cold solids and therefore is a measure of air–solid heat transfer [6,7]. Specific heat of air is calculated at the average of its inlet and exit temperatures. The mass flow rate of gas flow rate is estimated as the product of gas velocity, cross-sectional area and the density at the conditions corresponding to the location of orifice meter. Solids feed rate is determined by noting the time taken for feeding a measured quantity of solids. Solids exit temperature is calculated from the air–solid heat transfer rate as follows:

$$T_{s2} = T_{s1} + \frac{Q}{m_s C_{ps}} \tag{2}$$

Freitas and Freire [16] too estimated the solids exit temperature from the difference of heat lost by the gas and the heat transferred to annulus during gas–solid heat transfer in draft tube of a spouted bed. Heat transfer rate is related to heat transfer coefficient, heat transfer area and driving force as follows:

$$q = h_p A_h (\Delta T) \tag{3}$$

Since the objective of this work is to circumvent the use of heat transfer area in the calculations, heat transfer area (A_h) and heat transfer coefficient (h_p) are lumped to give a single parameter called thermal conductance.

Thermal conductance (product of heat transfer coefficient and heat transfer area) of a heat exchanger is determined from the heat transfer rate and driving as follows:

$$h_p A_h = \frac{q}{\Delta T} \tag{4}$$

Bandrowski and Kaczmarzyk [5] used log-mean temperature difference as a measure of driving force in vertical pneumatic conveying heat exchanger as this is similar to 1,1 heat exchanger operating in co-current mode. Therefore, ΔT in Eq. (4) is the log-mean temperature difference between air and solid as given below:

$$\Delta T = \frac{(T_{gin} - T_{s1}) - (T_{g2} - T_{s2})}{\ln\left(\frac{T_{gin} - T_{s1}}{T_{g2} - T_{s2}}\right)} \tag{5}$$

4.2. *Effect of solids feed rate on air–sand heat transfer rate and thermal conductance*

In gas–solid heat transfer systems involving solids flow, solids feed rate has been found to play a predominant role in determining the heat transfer rate. Jain et al. [17] reported that the gas–solid heat transfer rate in a cyclone heat exchanger increases initially with solids feed rate and reaches a maximum before decreasing further with solids feed rate. A few investigators including Rajan et al. [7], Freitas and Freire [16], Radford [18], Narimatsu et al. [19], Namkung and Cho [20] have observed an increase in gas–solid heat transfer rate with increase in solids feed rate in pneumatic conveying preheaters and dryers. The reasons attributed to these observations are (i) with increase in solids feed rate, solids volume concentration and hence the heat transfer area increase [16] (ii) At higher solids feed rates, heat capacity of solids is high leading to reduced temperature increase for solid phase temperature and hence the local driving force increases [7].

Fig. 1 shows the effect of solids feed rate on thermal conductance for heat transfer between hot air and cold particles of 390 μm at the air velocity of 5.75 m/s. Data are shown for both air–gypsum and air–sand heat transfer. It can be observed from Fig. 1 that thermal conductance increases with increase in solids feed rate. As evident from Eq. (4), thermal conductance is directly proportional to air–solid heat transfer rate. Increase in air–solid heat transfer rate with solids feed rate (data not shown here for brevity) leads to increase in thermal conductance with solids feed rate.

Thermal conductance may also be visualized as the reciprocal of thermal resistance. At high solids feed rates, due to increased solid volume concentration local air velocity may be increased owing to lower cross-sectional area available for air flow. This increase in air velocity would have led to increased turbulence resulting in reduced resistance for air–solid heat transfer. Hence resistance to air–solid heat transfer is expected to decrease with increase in solids feed rate.

4.3. *Effect of particle size on air–solid heat transfer rate and thermal conductance*

As briefed in Section 2, for constant solids feed rate and air flow rate, solids volume concentration increases with particle size. Heat transfer area (total external surface area of all particles in the duct) is a function of solids volume concentration and particle size [7]. Hence the effect of particle size on heat transfer area depends on the hydrodynamics of pneumatic conveying. Rajan et al. [6] and Rajan et al. [7] have explained the effect of particle size on air–solid heat transfer rate and thermal effectiveness from the information on solids holdup. Rajan et al. [6] have shown that the relative magnitude of rate of change of solids holdup with particle size and ratio of solids holdup to particle size determines the effect of particle size on heat transfer area. Higher heat transfer area at lower portions of the duct would increase heat transfer rate leading to a large temperature increase for solids; subsequently the driving force for heat transfer would decrease in the later portions of the duct. The air–solid heat transfer rates determined are the average heat transfer rates along the entire duct height. Hence different local heat transfer rates at various axial locations could result in nearly same average heat transfer rate for different particle sizes [7] as observed from Fig. 2 for air–sand heat transfer.

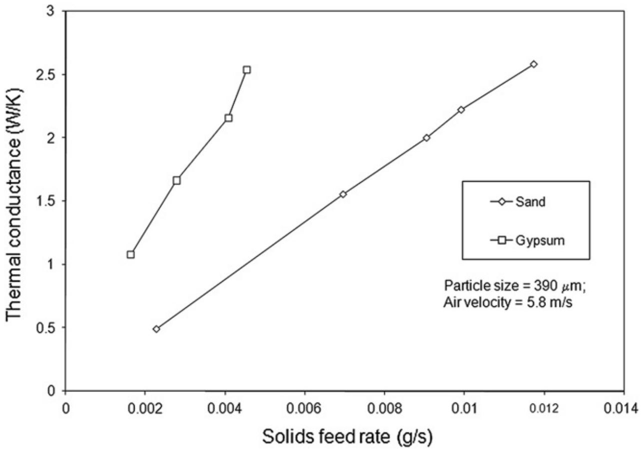

Fig. 1. Effect of solids feed rate on thermal conductance.

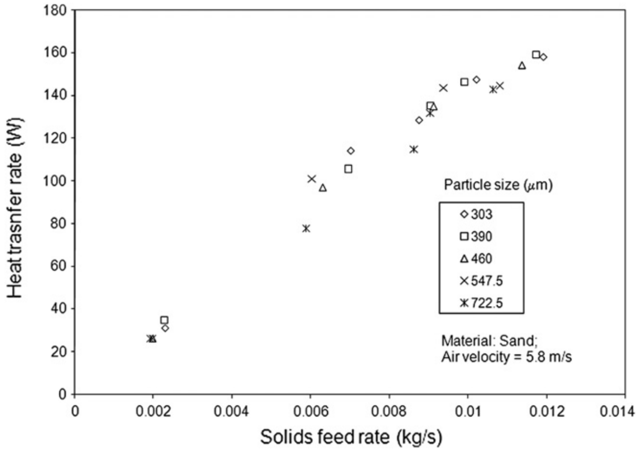

Fig. 2. Effect of particle size on air–solid heat transfer rate.

Fig. 3 shows the effect of particle size on thermal conductance of heat exchanger at the air velocity of 5.75 m/s. Data are again shown for both air–sand and air–gypsum heat transfer. It may be observed that the particle size has minimal effect on the thermal conductance of the heat exchanger for both the cases of air–sand and air–gypsum heat transfer. Since thermal conductance is directly proportional to the air–solid heat transfer rate, the trends of variation of thermal conductance with particle size are similar to that of variation of air–solid heat transfer rate with particle size.

4.4. *Effect of air velocity on thermal conductance*

With increase in air velocity for a fixed particle size at a constant solids feed rate, solid volume concentration decreases due to rapid particle acceleration by virtue of higher drag force. Hence heat transfer area decreases with air velocity for particles of a fixed size and solids feed rate. But increase in air velocity results in the presence of more amount of high temperature air. The later results in increase in air–solid heat transfer rate due to higher driving force while the former leads to decrease in air–solid heat transfer rate. The effect of air velocity on heat transfer rate depends on the magnitude of increase in driving force, increase in turbulence and decrease in heat transfer area. Using the same experimental setup under discussion, Rajan et al. [7] reported an increase in air–gypsum heat transfer rate with increasing air velocity and observed a maximum in heat transfer rate (at air velocity of 5.8 m/s), after which an increase in air velocity (typically above 6 m/s) led to reduction in heat transfer rate. Since the experiments on air–sand heat transfer were carried out at air velocities lower than 6 m/s, the air–gypsum heat transfer data obtained above the gas velocity of 6 m/s have been excluded in the present paper.

Fig. 4 shows the effect of air velocity on thermal conductance of heat exchanger for heat transfer between air and 460 μm size particles. Within the range of velocities reported in Fig. 4, increase in thermal conductance of the heat exchanger with increase in air velocity for air–gypsum and air–sand heat transfer may be attributed to the increase in air–solid heat transfer rate (due to higher driving force and turbulence overcoming low heat transfer area) with air velocity. However, the effect of air velocity on air–solid heat transfer is expected to depend on the hydrodynamic conditions prevailing in the column as well, as highlighted in the literature [7,20].

4.5. *Development of a correlation for thermal conductance*

A dimensionless group involving thermal conductance (h_pA_h) for pneumatic conveying heat exchanger could not be found in the literature to the best of our knowledge. Hence a dimensionless group (h_pA_h/k_gL) called dimensionless thermal conductance is introduced. The height of heat exchanger is chosen as characteristic dimension in this group, since axial profiles of solid volume concentration depend on the duct height. Particle Reynolds number $\mathrm{Re_p}$, solid loading ratio Fm and Fedorov number Fe [7] are defined as follows:

$$\mathrm{Re_p} = \frac{D_\mathrm{p} v_\mathrm{a} \rho_\mathrm{a}}{\mu_\mathrm{a}} \tag{6}$$

$$Fm = \frac{m_\mathrm{s}}{m_\mathrm{a}} \tag{7}$$

$$\mathrm{Fe} = D_\mathrm{p}\left[\frac{4g\rho_\mathrm{a}^2}{3\mu_\mathrm{a}^2}\left(\frac{\rho_\mathrm{s}}{\rho_\mathrm{a}} - 1\right)\right]^{1/3} \tag{8}$$

Additionally, ratio of volumetric specific heat of solid to gas (σ) given by Eq. (9) is used to take into account of solids specific heat and density.

$$\sigma = \frac{C_\mathrm{ps}\rho_\mathrm{s}}{C_\mathrm{p}\rho_\mathrm{a}} \tag{9}$$

Particle Reynolds number, solid loading ratio, Fedorov number,

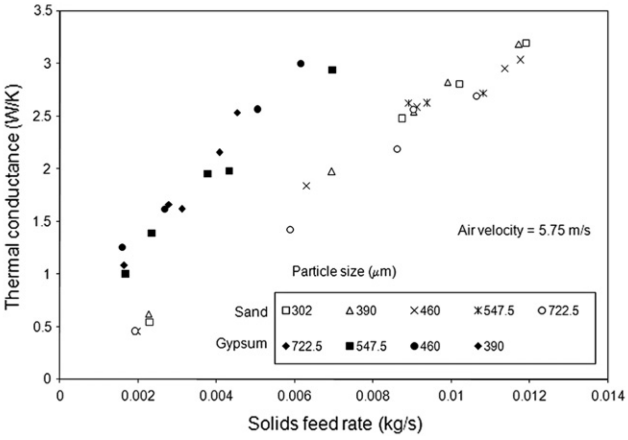

Fig. 3. Effect of particle size on thermal conductance.

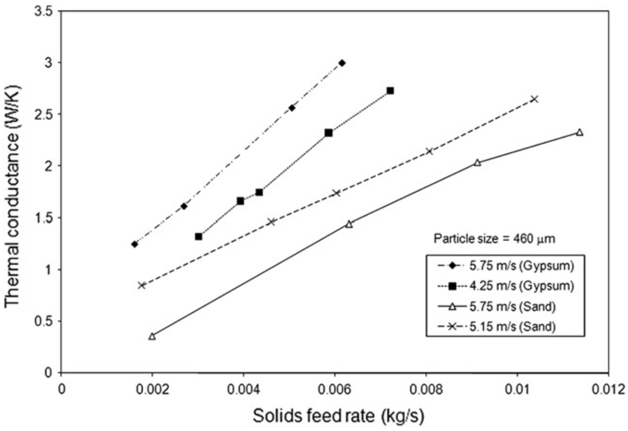

Fig. 4. Effect of air velocity on thermal conductance.

volumetric specific heat ratio may be related to dimensionless thermal conductance as follows:

$$\frac{h_\mathrm{p}A_\mathrm{h}}{k_\mathrm{g}L} = fn(\mathrm{Re_p}, Fm, \mathrm{Fe}, \sigma) \tag{10}$$

$$\frac{h_\mathrm{p}A_\mathrm{h}}{k_\mathrm{g}L} = b_0\mathrm{Re_p}^{b_1}Fm^{b_2}\mathrm{Fe}^{b_3}\sigma^{b_4} \tag{11}$$

Experimental data on thermal conductance collected in the present study were statistically analyzed to determine the coefficient (b_0) and exponents (b_1, b_2, b_3 & b_4). Statistical significance of the correlation coefficients b_0, b_1, b_2, b_3 & b_4 were determined by student t-test. Corresponding '*P*' values were closer to zero. Hence the correlation for thermal conductance of pneumatic conveying heat exchanger is given as

$$\frac{h_\mathrm{p}A_\mathrm{h}}{k_\mathrm{g}L} = 0.0126\mathrm{Re_p}^{1.3114}Fm^{1.0107}\mathrm{Fe}^{-1.4057}\sigma^{0.8089} \tag{12}$$

Equation (12) with the above coefficients fits the present experimental data on thermal conductance with a R^2 of 0.95 for 141 experimental data points (80 points for air–gypsum heat transfer & 61 points for air–sand heat transfer) within an error band of ±18% as evident from Fig. 5. The correlation encompasses a solid loading ratio range from 0.17 to 1.68, Fedorov number range from 7.61 to 26.80, particle Reynolds number range from 36.65 to 175.33, ratio of volumetric specific heat of solid to gas (σ) range from 1475 to 3035 and dimensionless thermal conductance range from 5.9 to 51. Thermal conductivity of solid has not been used in the correlation as its high value and small particle sizes lead to Biot numbers less than 0.25. It may be recalled that at such low values of Biot number, the internal resistance within the particle can be neglected and the resistance for heat transfer lies within the gas film surrounding the particles [6]. The proposed correlation could not be checked independently with the data of other investigators since lower gas velocities (less than 10 m/s) and small particle sizes (<800 μm) have been used in the present investigation compared to those reported in the literature. Also, much of the experimental data have been reported for pneumatic drying involving simultaneous heat and mass transfer [18–20] as against sensible heating of solids.

5. Conclusions

Experiments on air–solid heat transfer in vertical pneumatic conveying indicate that the thermal conductance of vertical pneumatic conveying heat exchanger increases with solids feed rate. Within the range of air velocity reported here, thermal conductance of heat exchanger increases with air velocity. Particle diameter has little influence on thermal conductance. In other words, under identical conditions of driving force, the heat transfer rate may be independent of particle size, essentially due to co-current nature of gas–solid flow, relatively long column ($L/D \sim 40$) and low solid loading ratios (<2). The proposed correlation for thermal conductance fits the present experimental data well. However, more experiments need to be conducted using different solid materials and duct geometry to fine tune the correlation such that the same may be used in the design/analysis of vertical pneumatic conveying heat exchanger provided the dimensionless numbers are in the range utilized for development of correlation.

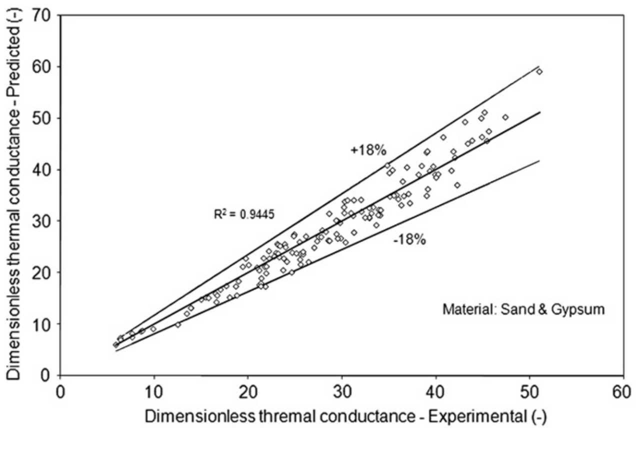

Fig. 5. Comparison between experimental dimensionless thermal conductance and dimensionless thermal conductance predicted using Eq. (12).

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