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Experimental study of thermal effectiveness in pneumatic conveying heat exchanger

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Abstract

Gas–solid interactions in pneumatic conveying are utilized to transfer heat between gas and solid phases. Experiments on air–solid heat transfer were carried out in a specially designed vertical pneumatic conveying test rig consisting of Galvanized Iron duct of 54 mm inner diameter and 2.2 m height, using gypsum as the solid medium and hot air as gas medium. Thermal effectiveness of air was found to increase with solids feed rate and decrease with air velocity. Thermal effectiveness of solids was found to decrease with solids feed rate. An optimum air velocity has found to exist at which the thermal effectiveness of solids is maximum. The effect of particle size on thermal effectiveness of air and solid is found to be predominant at higher solids feed rates. A dimensionless correlation has been developed for thermal effectiveness of solid which predicts the present experimental data within an error of ±12%.

Keywords: Pneumatic conveying heat exchanger; Thermal effectiveness; Correlation

1. Introduction

Gas–solid heat transfer is important in many industrial applications. Drying of granular materials is a very common operation in chemical, pharmaceutical, food industries etc. Frequently, the raw materials are preheated using exhaust flue gases. These operations involve heat transfer between gas and solids in packed beds or fluidized beds or in pneumatic conveying systems. Batteries of reverse flow cyclones with pneumatic conveying ducts connecting them are used to preheat raw meal (kiln feed) using exhaust gases from the cement kiln. The exit temperature of exhaust gases from the kiln is around 825–875 °C. Heat of these gases is used to preheat the cold solids feed in multistage cyclone separators with pneumatic conveying ducts between them, where the solids are conveyed pneumatically resulting in heat transfer between solids and gas. This ensures that raw meal is preheated and temperature of flue gas is reduced to around 320–350 °C. Jain et al. [1] presented industrial data on gas–solid heat transfer during pneumatic conveying between cyclone heat exchangers highlighting the potential energy savings through careful analysis of this system. Exposure of heat sensitive materials like food and pharmaceutical products to high-temperature for longer duration will result in the degradation and loss in the quality of the product. Drying of these products are achieved in pneumatic conveying dryers, which are continuous, convective dryers with dilute phase transport leading to short residence time of solids. Typical industrial applications using pneumatic conveying dryers include drying of alumina, polyvinyl chloride, calcium carbonate and iron ore [2–4] apart from animal feed, catalysts, cellulose, clay, corn fibers, epsum salt, gypsum, kaolin, pigment, poly propylene, poly styrene, proteins, silica, zeolites, etc. Other applications of gas–solid heat transfer in pneumatic conveying have been highlighted by Bandrowski and Kaczmarzyk [5] which include catalyst regeneration in fluid catalytic crackers, coal processing and high-temperature heat exchangers.

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Nomenclature

English symbols

a_0	constant in Eq. (11) (–)
a_1, a_2, a_3	exponents in Eq. (11) (–)
A_h	heat transfer area (m^2)
C_{ps}	specific heat of solid (J/kg K)
D	diameter of the duct (m)
D_p	particle diameter (m)
Fe	Federov number (–)
i	axial location of temperature sensor (m)
k_a	thermal conductivity of air (W/m K)
m_a	mass flow rate of air (kg/s)
m_s	solids feed rate (kg/s)
M_h	solids holdup (kg)
Q	experimental air–solid heat transfer rate (W)
R	solid–air heat capacity ratio (–)
Re_p	particle Reynolds number (–)
S_g	thermal effectiveness of gas or air (–)
S_s	thermal effectiveness of solid (–)
T_{g1}	steady state temperature of air in the duct in single-phase flow (°C)
T_{g2}	steady state temperature of air in the duct in two-phase flow (°C)
T_{gin}	temperature of air entering the solids feeding section (°C)
T_{s1}	temperature of solids feed (°C)
T_{s2}	steady state temperature of solids at the top of the duct (°C)
U_f	uncertainty in the measurement of variable '*f*'
v_a	average velocity of air in the duct (m/s)
$\frac{\partial f}{\partial X_j}$	sensitivity coefficient

Greek symbols

μ_a	viscosity of air (kg/m s)
ρ_a	density of air (kg/m^3)
ρ_s	density of air (kg/m^3)

Blasco and Alvarez [6] studied the drying of fish meal in a pilot plant pneumatic dryer using superheated steam as the hot medium and also predicted the performance of this system through simulations. Fyhr and Rasmuson [7] presented a model for pneumatic drying of wood chips using steam. The effect of cyclone on the kinetics of drying of paddy in a pneumatic dryer was studied by Kaensup et al. [8] who found that the dryer with cyclone produced a relatively lower final moisture content, higher evaporation rate and at lower specific energy consumption for evaporation of water. Kaensup et al. [9] studied the parametric effect of air velocity, solids feed rate and drying temperature on the pneumatic drying of rough rice with an initial moisture content of 22–26% on wet-basis. Narimatsu et al. [10] reported the drying of coarse porous alumina and sand particles in a pneumatic dryer. Computational investigations of pneumatic drying using one- and two-dimensional models have been reported by Matsumoto and Pei [11], Levy et al. [12], Levy and Borde [13], Pelegrina and Crapiste [14], Skuratovsky et al. [15] and Skuratovsky et al. [16] among others.

Despite the commercial importance of gas–solid heat transfer in pneumatic conveying, it is difficult to find appreciable information on the design and performance evaluation of these systems in the open literature owing to high patent value. Scarcity of gas–solid heat transfer studies in pneumatic conveying prior to 1978 resulted in Bandrowski and Kaczmarzyk [5] carrying out systematic study of heat transfer between hot air and ceramic spheres. They presented a correlation for prediction of gas-particle Nusselt number as a function of particle Reynolds number and solid volume concentration. Kudra et al. [17] measured gas-particle heat transfer coefficient in two-dimensional spouted beds while Freitas and Freire [18] measured gas-particle heat transfer coefficient in draft tube of a spouted bed, where the hydrodynamics are similar to that of a dilute phase pneumatic conveying. The present work addresses the effect of solid feed rate, particle size and air velocity on air–solid heat transfer in vertical pneumatic conveying heat exchanger. To enable plant engineers compute the exit temperatures of streams without iterations and to evaluate the pneumatic conveying heat exchanger, a correlation needs to be developed for prediction of thermal effectiveness in terms of dimensionless number requiring only the knowledge of gas and solid properties, superficial gas velocity and solids and gas mass flow rates which are easy to measure or obtain.

2. Experimental

A schematic diagram of the experimental setup is shown in Fig. 1. The experimental setup consists of a blower, a 100 mm inner diameter galvanized iron pipe fitted with heaters of 5 kW heating capacity, a venturi for dispersing solids, a pneumatic conveying duct and a cyclone separator for collection of solids. Bypass valves BV1 and BV2 are used to control the flow rate of air entering the heating section. A digital relay controller maintains a constant temperature of air leaving the heating section. A calibrated orificemeter connected to a U-tube manometer and fitted after the heating section is used to measure the air velocity and its flow rate. Solids feeding system consists of two-conical funnels of different dimensions and different orifice sizes at the apex. The larger cone is arranged in such a way that its orifice is at a fixed location inside the body of the smaller cone kept below. The larger orifice of the top cone ensures that the lower cone (smaller cone) is rapidly filled and solids height in the lower cone is maintained