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Natural convection heat transfer of hydrophilic particle suspension: Implications on nuclear waste remediation

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ABSTRACT

Natural convection of gel suspension has the potential to be applied to particulate recovery systems, such as in the dynamic filtering of radioactive waste particles. In this study, experiments were conducted to assess natural convection of gradually settling gelatin particle suspension in a rectangular cell, relative to single-phase natural convection with bulk temperature stratification, and to derive empirically a transfer relationship. The rectangular cell used had one vertical wall maintained at a lower temperature and the opposite wall at a relative thermal high. Two different sizes of gelatin particles were used. Local heat transfer coefficients were calculated from wall and bulk temperature measurements. Velocity field characteristics were determined using an Ultrasound Velocity Profiler (UVP). Heat transfer results showed both enhancement and de-enhancement in Nusselt number depending on temperature difference and particle size. The four necessary conditions to induce heat transfer enhancement in this setup and effect of sediment layer on heat transfer are discussed. The ultimate goal of this study was to examine a method of a dynamic filtering system that separated particles from wastewater using thermally-induced volumetric expansion and/or contraction of similarly sized functional gels that could be applied conceptually to nuclear waste remediation. For single-phase, the effect of thermal stratification on natural convection heat transfer can be accounted for by using a stratification factor, *S*, and for dual-phase, a stratified Nusselt number *sNu*. The reduction in the spread of data point relative to plotting Nu_y against Ra_y, indicates that plotting the stratified local Nusselt number, sNu_y, versus the local Rayleigh number, Ra_y, is appropriate. More importantly the analytical dependence to the Rayleigh number ($Ra_y^{1/4}$ for laminar and $Ra_y^{1/3}$ for turbulent) was preserved and within variations seen in the literature.

1. Introduction

Decontamination of effluents, such as wastewater that contains radioactive isotopes, heavy metals, or hazardous solid particulates, is a subject of great interest [1–4]. This interest has culminated in rapid growth of waste remediation and minimization directives and procedures. Typically, radioactive waste storage tanks contain hazardous and radioactive matter resulting from the production of nuclear materials, fuel, cladding etc. As the tanks age, the possibility of waste escaping to the environment increases. To minimize the risk of waste migration and exposure to workers, the public, and the environment, the waste must be retrieved and the tanks sealed. A primary remediation procedure for this kind of contamination is to separate metal particulates from the liquid waste. Since the thermal properties of each metallic constituent are different, a natural convection cell can be used to enhance separation. These mobile suspended particulates can therefore adhere to suspended materials like gels. Separating radioactive particles from liquid waste plays an important role in radioactive waste remediation since it reduces the volume of waste to be treated as radioactive. Moreover, if the most radioactive and long-lived isotopes could be greatly separated from a waste stream then the problems of storage and containments would be substantially simplified.

A dynamic filtering system can be used to recover particulate solids, such as radioactive particles, from a mixed waste stream using a class of gels, which swell and shrink in response to an applied temperature change. Several gels and gel-like materials are known to undergo an abrupt change, or phase transition, between collapsed and swollen states depending on their composition. For example, poly(acrylamide) swells with increasing

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Nomenclature

Symbol	Description
A	aspect ratio $[H/L]$
c	velocity of ultrasound in the two-phase flow
$\bar{d}$	number-average particle diameter
d_p	gelatin particle size (µm)
f_i	fraction in the class range
f_d	doppler frequency shift
f_0	ultrasound frequency
g	gravitational acceleration (m/s^2)
H	the distance between two horizontal walls
k	thermal conductivity (W/m K)
L	the distance between hot and cold walls
L_1	thickness of the aluminum tube wall
L_2	thickness of the aluminum tape
n_i	number of particles
Nu	Nusselt number $[hH/k]$
Nu_y	local Nusselt number $[hy/k]$
Pr	Prandtl number $[\nu/\alpha]$
q''_x	heat flux at x (W/m^2)
Ra	Rayleigh number $[g\beta\Delta TH^3/\nu\alpha]$
Ra_H	Rayleigh number based on the cell height H $[g\beta\Delta TH^3/\nu\alpha]$
Ra_y	local Rayleigh number $[g\beta\Delta Ty^3/\nu\alpha]$
S	stratification parameter $[(T_{top} - T_{bottom})/(T_{wall,y} - T_{bulk,y})]$
S_{ave}	average stratification parameter
sNu_y	local stratified Nusselt number $[Nu_y/(1+S)^{1/4}]$
t	time lapse between the emission and reception of ultrasound pulses
T	local temperature in °C
T_{bottom}	bulk temperature at the bottom of the cell (°C)
T_{bulk}	Bulk temperature (°C)
T_{cold}	cold wall temperature (°C)
T_{film}	film temperature, $[(\bar{T}_{hot} + \bar{T}_{cold})/2]$ (°C)
T_{hot}	hot wall temperature (°C)
T_{inside}	inside surface temperature of the aluminum tube (°C)
$T_{surface}$	surface temperature of the aluminum tube (°C)
ΔT	temperature difference $[T_{hot} - T_{cold}]$ (°C)
T_{top}	bulk temperature at the top of the cell (°C)
T_{wall}	wall temperature (°C)
$\bar{T}_{bulk}$	average bulk temperature (°C)
$\bar{T}_{cold}$	average cold wall temperature (°C)
$\bar{T}_{hot}$	average hot wall temperature (°C)
u	fluid velocity component perpendicular to the hot wall
u_p	velocity of the particles within the convective cell

Greek letters

α	thermal diffusivity (cm^2/s)
β	thermal expansion coefficient (K^{-1})
σ	standard deviation

temperature, while poly(*N*-alkyl substituted acrylamide) swells with decreasing temperature. These changes can occur in response to minute changes in their physical environment, such as, temperature, solvent composition, pH, ionic strength, light and electric field [5–12]. These functional materials have been studied for many purposes, including, controlled drug delivery, filtration at molecular level, extraction solvents for proteins, and concentration of dilute suspensions [13–19]. Some of these materials can be obtained from polymers that exhibit lower critical suspension temperatures (LCST). Examples of these include and are not limited to polyethylene oxide, hydroxypropyl cellulose, polyvinyl alcohol and derivatives of poly acrylamides [19].

Natural convection with particles is different from that of single-phase natural convection and is regarded as two-phase flow. Two-phase flows consist of liquid–liquid, liquid–gas, liquid–solid particles, or gas–solid particles. In liquid–solid particles suspension, particles will tend to settle out of suspension and sediment in most cases. The bottlenecks experienced in any analyses arise due to this settling further contributing to a quantitative complication. Sedimentation of particles and natural convection can occur simultaneously. Sedimentation and suspension flows are of importance, especially in the field of solid–liquid separations in the chemical, mining, pulp and paper, wastewater, food, pharmaceutical, ceramic and other industries. Also, the sedimentation of particles from a convecting fluid is a process of much interest to engineers, fluid dynamicists, geologists and metallurgists. For example, the process plays a fundamental role in controlling the settling behavior of phenocrysts in magma chambers, crystals and impurities in metallic castings and carbon microparticles in combustion chambers [20]. Although intensively studied for many years, an understanding of sedimentation and suspension flows is still far from complete.

Unlike single-phase flow, suspension flow introduces a number of additional features, including properties of suspensions (rheology, particle size and shape, particle–particle interaction, surface characteristics, yield stress, concentration, viscosity), individual particles (orientation and surfactants), and sediments (permeability, porosity and compressibility). Studies on two-phase liquid–solid flows and suspensions in relation to settling and focused on hydrodynamics have been reported [21–33]. Koyaguchi et al. [20] investigated sedimentation of silicon carbide particles from a convective fluid experimentally by using a tank heated from below. They showed that convective motion due to heating from below can be affected by the presence of particles and is controlled by the bulk density of a particulate suspension. Stommel [21] investigated trajectories of the particles sinking slowly through convection cell, which is heated from below, analytically. He classified the trajectories of particles in terms of the quantity, which is the ratio of the settling velocity to the maximum upward water velocity. Most of these studies have primarily dealt with the convective motion due to heating from below.

For liquid–solid particle flow it is also recognized that suspensions of solid particles have great potential to enhance the heat transfer. For two-phase gas–solid particle flow, Murray [34] investigated the mechanisms associated with the enhancement of heat transfer over the front of a tube in a gas-particle cross flow. Plass and Molerus [35] investigated wall-to-suspension heat transfer of solid–liquid pipe flow. In order to clarify how particle in suspension affect the structure of flow, Zisselmar and Molerus [36] investigated solid–liquid pipe flow with regard to turbulence modification using laser-Doppler anemometry. They concluded that the intensity of turbulence is significantly affected by the size of the solid particles. Moreover, as the size of the particles increased, the turbulence intensity was dampened depending on solids concentration as well as on distance from the wall. Mechanisms of heat flow in such suspensions have also been studied using nano-sized particles (see [37]). These nano-sized particles are also referred to as nanofluids. Khanafer et al. [38] investigated heat transfer enhancement in an enclosure utilizing these nanofluids. They concluded that the suspended nano-sized particles