Heat transfer from spiral tubes in an air fluidized bed
by David Walter Everly

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Chemical Engineering
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Abstract:
The primary objective of this investigation is to present information on heat transfer from spiral copper tubes to an air fluidized bed. A cylindrical Plexiglass column, 14 inches in diameter and 12 feet in height, and glass beads as the solid particles were used. The experimental variables were particle diameter (0.0076 inches to 0.0164 inches), air flow rate (65 pounds per hour to 550 pounds per hour), and number of ridges (3,5) on the spiral copper tubes. A coiled configuration of the spiral tubes was used. The heat transfer coefficients increased with decreasing particle diameter and increasing air flow rate. For the smaller diameter particles, a leveling off or maximum of heat transfer coefficients was observed at higher air flow rates. The spiral tube with three ridges had higher heat transfer coefficients than the one with five ridges. However, the comparative performance to bare tubes was similiar for both spiral tubes. A 45 per cent increase in performance over bare tubes using spiral tubes and the 0.0164 inch diameter particles was recorded. A correlation was formulated which fit the data within the range of experimental error.

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ABSTRACT

The primary objective of this investigation is to present information on heat transfer from spiral copper tubes to an air fluidized bed. A cylindrical Plexiglass column, 14 inches in diameter and 12 feet in height, and glass beads as the solid particles were used. The experimental variables were particle diameter (0.0076 inches to 0.0164 inches), air flow rate (65 pounds per hour to 550 pounds per hour), and number of ridges (3,5) on the spiral copper tubes. A coiled configuration of the spiral tubes was used. The heat transfer coefficients increased with decreasing particle diameter and increasing air flow rate. For the smaller diameter particles, a leveling off or maximum of heat transfer coefficients was observed at higher air flow rates. The spiral tube with three ridges had higher heat transfer coefficients than the one with five ridges. However, the comparative performance to bare tubes was similiar for both spiral tubes. A 45 per cent increase in performance over bare tubes using spiral tubes and the 0.0164 inch diameter particles was recorded. A correlation was formulated which fit the data within the range of experimental error.

INTRODUCTION

Fluidized beds have an increasing number of applications in a wide range of industrial operations. Several applications are drying, calcining, mixing, cooling towers, catalytic reactors, coating, and removal of fines from bed particles. A fluidized bed is a column that contains solid particles that rest on a distributor plate at the bottom of the column. A fluidizing mass, gas or liquid, is passed up through the bottom of the column. Starting with low mass velocities of a gas, for example, passing up through the bed, there is no movement of the solid particles. As the gas velocity is increased, the pressure drop across the bed increases. At the point when the pressure drop across the bed of solid particles equals the weight of the solid particles and the friction of the particles at the side of the column, the bed will expand. This is called the minimum fluidization velocity. The particles separate and some particle movement begins, but there is no bubbling. After this point, an increase in gas velocity causes the particles to separate more forming larger pores and channels in the bed. Bubbles now begin to rise through the bed. As the bubbles rise, they expand and burst at the surface of the bed. The bed now visually resembles a contained "boiling liquid"(1). The expansion in the bed is not uniform.

The size and number of bubbles increase as the gas flow increases and also as the height above the distributor plate increases. This is also a function of the geometry of the bed, column diameter, and distributor plate design(2). There is vigorous bubbling in the bed and mixing of the solid particles. This is known as the aggregative or "bubble" regime, the type of fluidization encountered in most applications. As fluidizing mass velocities are increased still further, the bed becomes unstable resulting in massive slugging and surges. This can increase to the point where the solid particles are blown out of the top of the column.

The chemical and petroleum industries use fluidized beds as a catalytic reformer(3), catalytic cracking. Gasification of powdered coal for combustion and conversion has fluidized bed application. Fluidized beds are being used in coating of metal parts with thermoplastic resins, a heat exchanger for geothermal energy, water purification, waste heat and nuclear waste disposal, and the drying of iron ore.

Some of the physical advantages of a fluidized bed are uniform temperature and solid particle mixing throughout the bed (much higher heat transfer coefficients than forced convection), drying of solid particles, gas mixing, removal of fines from bed particles, and ability to continually recycle or add solid particles to the bed. Another advantage is low capital and maintainence costs. Since a fluidized bed is a stable system that can be operated at steady state, ease of operational control is important. Flexibility of materials that may be used is another advantage.

There are also some disadvantages that are characteristics of fluidized beds. The very active particle movement may cause erosion of column walls, immersed surfaces, and the solid particles. Difficulty is found in fluidization of very sticky materials that can be used in a fluidized bed operating in the bubble regime.

There are many applications where heat is extracted or added to the fluidized bed. This was originally accomplished by heat transfer through the walls of the column. Later, tubes were immersed in the fluidized bed for heat transfer because of the increased surface area. Much research has been done in this area in an effort to establish reliable design criteria. Some research has been done using tubes with extended surfaces. It has been possible to improve heat transfer rates with extended surfaces. The purpose of this investigation is to present information on the heat transfer coefficients of spiral copper tubing. The spiral copper tubing has previously been used in heat exchanger applications.

THEORY AND PREVIOUS RELATED RESEARCH

The section on theory and previous related research has been divided into the mechanism of fluidization for heat transfer and previous related research.

Mechanism of Fluidization for Heat Transfer

The study of the aggregative or "bubble regime in fluidized beds, including bubble size and behavior and solid particle motion, has been done by several reseachers (3,4,5,6). These include attempts to model analytically the physical characteristics of a fluidized bed. The models have different ranges where the nonideal behavior of a fluidized bed is considered. Mass transfer and heat transfer in fluidized beds cannot necessarily be described by the same model. There have been several models proposed for heat transfer between fluidized beds and surfaces.

A "film" model presented by Levenspiel and Walton(4) describes a thin laminar film of fluidizing gas next to the surface which is the controlling heat transfer resistance. The activity of the solid particle against this film is the model's explanation of increased heat transfer coefficients. A "packet" model presented by Mickley and Fairbanks(8) is described as "packets" of particles coming into contact with the surface for a short time period, unsteady state heat transfer is the controlling resistance. The "packet" then leaves the surface and returns to the bulk medium to dissipate the heat.

A modification of this theory was presented by Ziegler, Koppel, and Brazelton(9) and extended by Genetti and Knudsen (10). Assuming constant physical properties of the solids and fluids and spheres of uniform diameter for the solid particles, the mechanism proposes that particles from the bulk medium at temperature T_b come into contact with the surface at temperature T_w. Heat is transfered by convection from the surrounding fluid to the particle for a length of time, θ. The fluid temperature, T_f, is assumed to be the arithmetic mean of T_w and T_b. After time θ, the particle returns to the bulk medium to dissipate the heat. This mechanism is shown on Figure 1. The conduction heat transfer at the point of contact with the surface and the radiant heat transfer from the surface are neglected. They found that the following formula describes the rate of heat transfer from a surface in a fluidized bed.

$$Nu_p = \frac{h_o D_p}{k_g} = \frac{7.2}{\left[1 + \frac{6 k_g \theta}{\rho_s C_{ps} D_p^2}\right]^2}$$

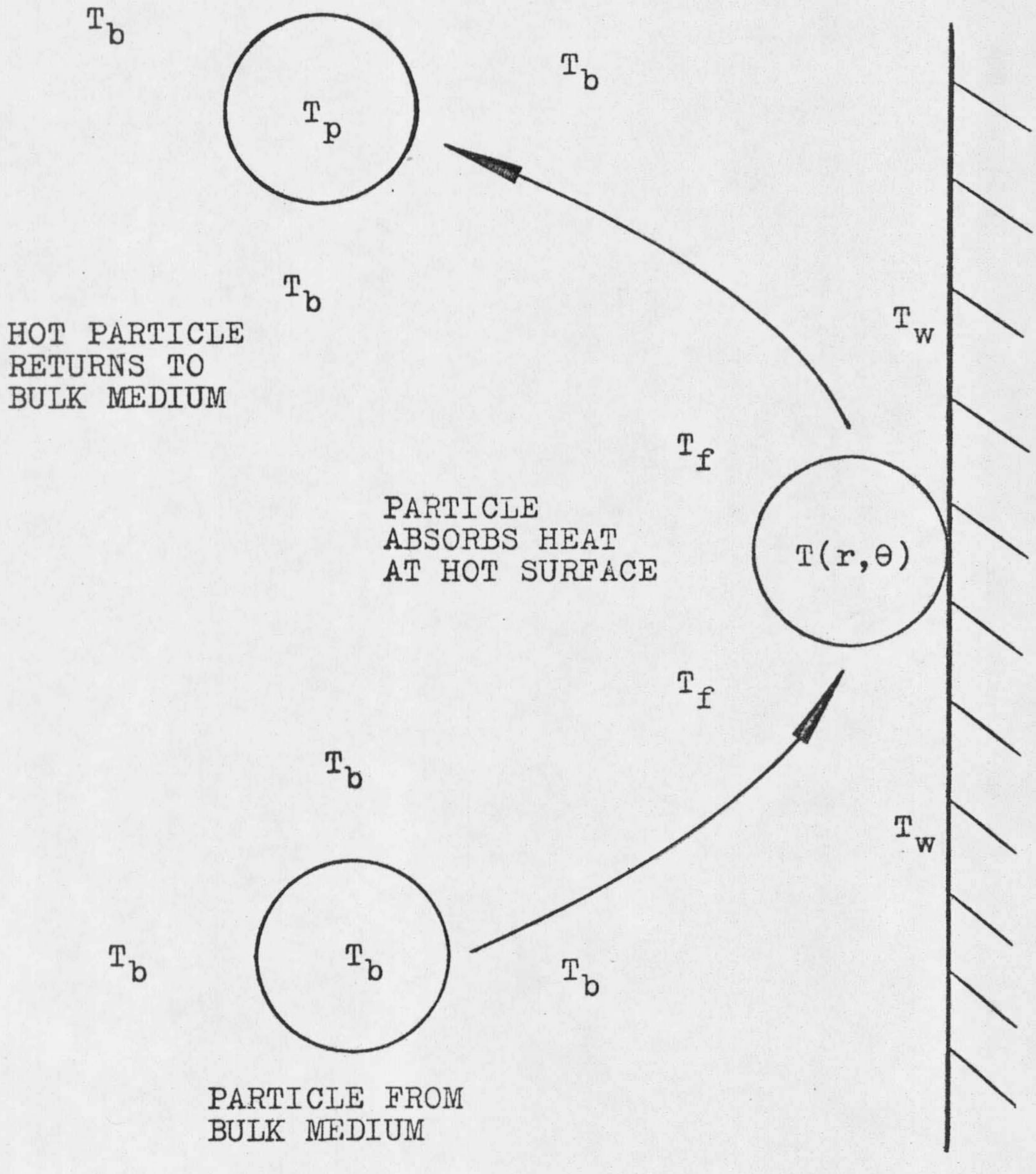

FIGURE 1. PROPOSED HEAT TRANSFER MECHANISM

where,

Nu_p = particle Nusselt number, dimensionless

h_o = heat transfer coefficient, BTU/ft^2-hr-^oF

D_p = particle diameter, ft

k_g = thermal conductivity of fluidizing medium, BTU/hr-ft-^oF

θ = average contact time, hr

ρ_s = density of solid particles, lbs/ft^3

C_{ps} = heat capacity of solid particles, BTU/lb-^oF

Genetti and Knudsen recommended that $10(1-\epsilon)^{0.5}$ be substituted for 7.2 in the above equation, where $(1-\epsilon)$ is the particle fraction, dimensionless. The data collected in this study was correlated using this formula. Kunii and Levenspiel(3) have compared models and suggested a general model which includes the different mechanisms.

Previous Related Research

There have been numerous papers published that have information concerning heat transfer from immersed surfaces. Most papers include a study of the effect of particle diameter. Other work includes studies of the effect of particle shape, density, and heat capacity, fluid thermal conductivity, viscosity, void fraction, and mass velocity. Chen and Withers(13,14) studied the heat transfer characteristics of vertical bare and finned tubes in a fluidized bed varying fin height and fin spacings. They report that gains as large as 190 per cent for heat transfer coefficients for helical copper fin tubes compared to plain tubes.

Bartel and Genetti(15) studied heat transfer from a horizontal bundle of carbon steel bare tubes and finned tubes to a bed of glass beads fluidized with air. Varying parameters were fin height, distance between tubes, particle diameter, and air mass velocity. Gains up to 80 per cent compared to bare tubes were observed. Priebe and Genetti (16) studied heat transfer from horizontal discontinuous finned tubes and spined tubes as a function of spines per turn and spine height. For copper spines, gains up to 60 per cent were observed.

Kratovil(17) studied heat transfer from a horizontal bundle of continuous, helical copper finned tubes as a function of fin height, fin spacing, and particle diameter. Gains as large as 190 per cent compared to bare tubes were recorded for certain conditions.

EXPERIMENTAL PROGRAM

The primary objective of this investigation was to determine the effect of the number of ridges and the magnitude of the heat transfer coefficients of the spiral copper tubes. The parameters that should effect the heat transfer coefficients are the properties of the fluidized bed, the operating conditions, and the geometry of the equipment. The properties of the fluidized bed are the solid particle size, shape, and composition and the fluidizing medium. The operating conditions are the velocity of the fluidizing medium, the height of particles in the bed, and the inlet temperature and mass flow rate of the medium used to transfer heat from inside the spiral copper tubes. The equipment geometry includes the diameter, the number and depth of the ridges, and the location of the spiral copper tubes and the shape of the column. Four of these parameters are the experimental variables: particle size, velocity of the fluidizing medium, the number of ridges on the spiral copper tube, and the mass flow rate of the medium used to transfer heat from inside the copper tubes.

Air was used as the fluidizing medium. The inlet air temperature was consistantly in the range of 98 ^{o}F to 115 ^{o}F, therefore, the physical properties of the inlet air to the column were nearly constant. Spherical glass beads were used as the bed particles. The density of the glass is approximately 155 lbs/ft^3, and the glass beads were screened before the final data was collected. Water was used as the medium transferring heat from inside the spiral copper tubes. Data was collected for two different spiral copper tubes (3,5 ridges). The following table is a list of the physical characteristics of the spiral tubes used in this study.

Table 1. Description of Spiral Tubes

	Tube 1 (HTRI 1)	Tube 2 (HTRI 16)
wall thickness	20 gauge	20 gauge
material	copper	copper
length	6 ft (including short plain ends)	6 ft (including short plain ends)
number of ridges	5	3
pitch	2 inches	2.8 inches
groove depth	.15 inches	.21 inches
outer diameter	1-1/8 inch OD	1-1/8 inch OD

The number of ridges on the spiral tubes includes a variable distance between the ridges. This distance was not given in the manufacturer's description of the tubes, but there was sufficient data for each tube to calculate a value for this distance. The distance between ridges was

was calculated as .3513 inches for Tube 1 and .7069 inches for Tube 2. This variable was included in determining the final correlation. The range of the four experimental variables is given in Table 2.

Table 2. Range of Experimental Variables

Variable	Range
Particle size	.0076,.0109,.0164 inch diameter
Air mass velocity	60 to 560 lbs/hr-ft^2
Number of ridges	3,5
Water flow rate	95 to 540 lbs/hr

All of the other parameters were held at constant values which will be described in the following.

EXPERIMENTAL EQUIPMENT

The equipment used in this investigation is divided into three types: the fluidizing system, the thermocouple system, and the tube and water heating system. A schematic drawing of the overall experimental system is shown in Figure 2. A photograph of the column and surrounding equipment is shown on Figure 3.

Fluidizing System

The main parts of the fluidizing system are the column, funnel, distributor plate, air blower, and glass beads.

The column was constructed of a cylindrical, clear Plexiglass that was 3/8 inch thick. The column was 13-1/2 inches inside diameter and 8 feet 9 inches in height. A detail view of the column is shown on Figure 4. The column was divided into two sections that could be separated to make it possible to change the spiral tubes. The lower section was 25-3/4 inches and the upper section was 79-1/4 inches. A 1-3/4 inch flange of 3/4 inch thick Plexiglass was connected to the ends of each section to enable the sections to bolt together. All sections of the column were fitted with rubber gaskets. The top of the column was a removable 1-3/4 inch wooden ring, 3/4 inch thick, with a 13-1/2 inch inside diameter. The center of the lid was covered with stainless steel screen (1/32 inch openings). To aid in removing the glass beads between runs, a 4-1/2 inch inside diameter port (made of 1/4 inch Plexiglass) was connected to the wall of the column. The column was supported by a wooden frame that was bolted to a concrete floor.

A funnel section made of 1/32 inch galvanized steel was used as the bottom of the column. The cone section of the funnel had a top inside diameter of 13-1/2 inches, a bottom inside diameter of 2 inches, and a height of 10 inches. The spout of the funnel was 2 inch diameter and 4 inches in length.

The distributor plate consisted of a piece of 100 mesh stainless steel wire cloth between two 1/16 inch stainless steel perforated plates (perforations were 1/8 inch diameter and 3/16 inch center-to-center). The distributor plate was 17 inches in diameter and was fitted with rubber gaskets. A particle drain pipe, 1 inch outside diameter, was connected to the distributor plate and extended through the side of the funnel section. A quick opening valve on the end of the pipe was used to empty the column of the glass beads.

Air was supplied to the column with a Sutorbilt blower driven by a 7½ HP Brown-Brockmeyer electrical motor. The air was blown through a 2-1/2 inch schedule 40 steel pipe that was connected by a rubber hose to the stem of the funnel section under the column. A gate valve in the main line and a gate valve in a 2 inch bypass line which vented air to the atmosphere were used to regulate the air flow rate. The supply valve was left completely open. The air flow rate was controlled by throttling the bypass valve and it was measured using an orifice and water manometer in the supply line. The orifice had a 1-1/2 inch diameter opening and vena contracta pressure taps. The pressure drop across the orifice was measured with a water manometer. A Duragauge pressure gauge located between the orifice and the column was used to measure the pressure of the air entering the column.

The pressure drop across the fluidized bed was measured with a water manometer. The pressure taps were placed 16 -3/4 inches apart, the lower tap was 2 inches above the distributor plate.

Glass beads were used as the solid particles in the bed. A static bed height of 20 inches was a constant for all runs. An analysis of the glass beads is included in the following material.

Thermocouple System

The lead wires from the seven thermocouples were wired into an eleven position switch box mounted on a panel board. The switch box was connected to a Honeywell chart recorder from which temperatures could be read directly in ^{o}F. The thermocouples were iron-constantan (type J, B and S gauge-30). The location of the three bed thermocouples is shown on Figure 3. A single thermocouple was placed on the outer surface of the Plexiglass column, in the air stream entering the column, and in the inlet and outlet water streams. The thermocouple readings were assumed accurate to $\pm$ 0.5 ^{o}F.

Tube and Water Heating System

Two six foot lengths of the spiral copper tube were fitted together and bent into a 7 inch inside diameter coil. A photograph of the coil for Tube 1 is shown in Figure 5. The upper end of the coil was fitted to a 1 inch diameter steel pipe going through a hole in the column wall, 19 inches above the distributor plate. The lower end of the coiled tube was fitted to a 1 inch diameter pipe that went through a hole in the wall of the column, 2-1/2 inches above the distributor plate, and led to a discharge area where the water flow rate could be measured. This is measured by weighing the amount of water discharged over a set period of time. The average distance between turns of the coil was 2-3/4 inches. The holes where the inlet and outlet water pipes went through the column walls were sealed with Permatex silicone sealant. Water from an overhead tnak was heated by steam in a countercurrent heat exchanger and used as the inlet water to the coiled tube in the bed.