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ENHANCEMENT OF HEAT TRANSFER IN FLUIDIZED BED COMBUSTOR USING HEAT PIPE-HEAT EXCHANGER

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ABSTRACT

Heat pipe-heat exchanger is introduced as an innovative and enhanced technique to transfer heat from the fluidized bed combustor in industrial applications. The study presents the fluidized bed combustor as melting furnace of metals using heat pipe-heat exchanger. The study is achieved by introducing a mathematical model that connects and simulates the processes of fluidization of inert-solid particles, combustion of gaseous fuel and heat transfer by the heat pipe-heat exchanger to different types of thermal loads. These processes are considered through a system of fluidized bed combustor using gaseous fuel and using heat pipe-heat exchanger at steady state conditions, based on the following assumptions: two-phase theory of fluidization describes the fluidized bed, the fluidized bed combustor is assumed to be an ideally stirred isothermally tank reactor for both gas and solid phases, the complete combustion describes the combustion process that is completely achieved through the bed, the evaporators length equals the expanded bed height, while the condenser sections have a constant length, heat transfer is shared equally among the heat pipes and it is determined by the minimum heat transfer limits. The mathematical model is experimentally verified for two different types of thermal loads that liquid water and molten wax, a quit agreement was found. The theoretical results showed that, by using heat pipes-heat exchanger, about 57 % of 10 kW fluidized bed combustor is transferred and produces more than 8 Lit/hr of molten zinc at 600.0 ^{o}C, where the optimum operating conditions for the number of heat pipes is 2, filling ratio is 0.3, particle size is 0.5 mm.

KEYWORDS:
Fluidized Bed Combustor – Heat Pipe – Heat Exchanger – Molten Metal

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Contents

NOMENCLATURE

LIST OF ALPHAPITICAL SYMBOLS

Symbol	Definition	Unit
A_{cf}	Cross sectional inner flow area of cooling fluid through the heat sink	m^2
A_{eo}	Outer surface area of the evaporator section	m^2
A_{flow}	Cross sectional inner area of the fluidizing column	m^2
A_{hp1}	Cross sectional inner area of the thermosyphon	m^2
Ar	Archimedes number of the fluidizing particles at fluidization $Ar = \frac{d_p^3 \rho_g (\rho_p - \rho_g) g}{\mu_g^2}$	
A_x	Cross sectional area of the wall of the thermosyphon	m^2
C_1, C_2	Constants of Minimum Fluidization Velocity	
C_{cw}	Correction factor of cooling water flow meter	
C_d	Orifice discharge coefficient	
C_f	Correction factor of fuel flow meter	
Cp_a	Specific heat of inlet fluidizing air	J/kg.K
Cp_g	Specific heat of the fluidizing gas	J/kg.K
Cp_l	Specific heat of the liquid film	J/kg.K
Cp_p	Specific heat of the fluidized particles	J/kg.K
C_w	Specific heat of the cooling fluid	J/kg.K
C_xH_y	Hydrocarbon gaseous fuel	
D_{eff}	Effective diameter of the fluidizing column	m
D_{bed}	Inner fluidizing column diameter	m
d_b	Bubble diameter	m
d_{bm}	Maximum bubble diameter	m
d_{bo}	Initial bubble diameter	m
d_{hs}	Inside hydraulic diameter of shell	m
d_i	Inside diameter of the thermosyphon	m
d_o	Outside diameter of the thermosyphon (immersed tube)	m
$d_{orifice}$	Orifice inside diameter	m
d_p	Size of fluidized particles	m
d_s	Inside diameter of shell	m
Error F_{Exp}	Error in experimental output result	
F	Filling ratio of the thermosyphon	
F_{bf}	View factor between the bed upper surface and the freeboard	
F_{Exp}	Experimental output result	
F_{ins}	View factor of the outer surface of the insulating material to the atmosphere	

$\mathbf{F_{True}}$	True experimental result	
$\mathbf{f_b}$	Bubble frequency	$1/m^2.s$
Gr	Grashoff number for free convection between the outer surface of the insulating material and the atmosphere	
g	Gravitational acceleration = 9.81	m/s^2
$\mathbf{H_{air}}$	Enthalpy of the inlet fluidizing air	W
$\mathbf{H_{flue}}$	Enthalpy pf Flue Gases	W
$\mathbf{H_{mf}}$	Minimally fluidized bed height	m
$\mathbf{H_o}$	Static bed height	m
$\mathbf{H_f}$	Fluidized bed height	m
$\mathbf{h_{atm}}$	Heat transfer coefficient between the outer surface of the insulating material and the atmosphere	$W/m^2.K$
$\mathbf{h_{be}}$	Heat transfer coefficient from the fluidized bed to the immersed tubes (evaporators)	$W/m^2.K$
$\mathbf{h_{bw}}$	Heat transfer coefficient between the fluidized bed and fluidizing column	$W/m^2.K$
$\mathbf{h_c}$	Condensation heat transfer coefficient	$W/m^2.K$
$\mathbf{h_{cc}}$	Conductive and convective components of the heat transfer coefficient between the fluidized bed and fluidizing column	$W/m^2.K$
$\mathbf{h_{cond}}$	Conductive component of the heat transfer coefficient from the fluidized bed to the immersed tubes (evaporators)	$W/m^2.K$
$\mathbf{h_{conv}}$	Convective component of the heat transfer coefficient from the fluidized bed to the immersed tubes (evaporators)	$W/m^2.K$
$\mathbf{h_e}$	Evaporation heat transfer coefficient	$W/m^2.K$
$\mathbf{h_{fg}}$	Latent heat of the thermosyphon working fluid	J/kg
$\mathbf{h_{fi}}$	Heat of formation of chemical species i	J/kmole
$\mathbf{h_{rad}}$	Radiative component of the heat transfer coefficient from the fluidized bed to the immersed tubes (evaporators)	$W/m^2.K$
$\mathbf{h_{radatm}}$	Radiative Heat transfer coefficient between the outer surface of the insulating material and the atmosphere	$W/m^2.K$
$\mathbf{h_{radw}}$	Radiation component of the heat transfer coefficient between the fluidized bed and fluidizing column	$W/m^2.K$
$\mathbf{h_{sink}}$	Heat transfer coefficient of heat sink	$W/m^2.K$
$\mathbf{K_p}$	Equilibrium constant	
$\mathbf{L_a}$	Length of adiabatic section	m
$\mathbf{L_c}$	Length of condenser section	m
$\mathbf{L_e}$	Length of evaporator section	m
$\mathbf{L_{sector}}$	Height of the combustion sector = 0.1	m
$\mathbf{M_a}$	Mass flow rate of fluidizing air	kg/s
$\mathbf{M_{cw}}$	Mass flow rate of the cooling fluid	kg/s
$\mathbf{M_f}$	Mass flow rate of fuel	kg/s

N	Number of thermosyphons	
$\mathbf{N_i}$	Number of atoms of chemical species i	Atoms
$\mathbf{N_{or}}$	Number of holes in the distributor grid	
$\mathbf{Nu_c}$	Nusselt number of the condensation inside the thermosyphon	
$\mathbf{Nu_e}$	Nusselt number of the evaporation inside the thermosyphon	
$\mathbf{n_i}$	Number of kmoles of species i	kmoles
P	Pressure of the working fluid inside the thermosyphon	Pa
$\mathbf{P_{atm}}$	Atmospheric Pressure	Pa
$\mathbf{P_p}$	Pressure of the liquid pool inside the thermosyphon	Pa
Pr	Prandtle number for free convection between the outer surface of the insulating material and the atmosphere	
$\mathbf{Pr_g}$	Prandtle number of fluidizing gas	
$\mathbf{Pr_l}$	Prandtle number of the liquid film inside the thermosyphon	
$\mathbf{Pr_w}$	Prandtle number of cooling water	
$\mathbf{P_v}$	Pressure of the vapor inside the thermosyphon	Pa
$\mathbf{Q_1}$	Heat transfer by thermosyphons	W
$\mathbf{Q_2}$	Heat transfer through fluidizing column	W
$\mathbf{Q_3}$	Energy of Flue Gases	W
$\mathbf{Q_{boiling}}$	Boiling heat transfer limit of thermosyphon	W
$\mathbf{Q_{combustion}}$	Heat liberated from the combustion process	W
$\mathbf{Q_{dic}}$	Heat transfer by a direct immersed coil	W
$\mathbf{Q_{dryout}}$	Dryout heat transfer limit of thermosyphon	W
$\mathbf{Q_{ent}}$	Entrainment heat transfer limit of thermosyphon	W
$\mathbf{Q_{flue}}$	Heat transfer with the flow of flue gases	W
$\mathbf{Q_{hp1}}$	Heat transfer by one thermosyphon	W
$\mathbf{Q_{radgf}}$	Heat transfer by radiation between the fluidizing gas to the inner surface of the freeboard	W
$\mathbf{Q_{radpf}}$	Heat transfer by radiation between the fluidized particles to the inner surface of the freeboard	W
$\mathbf{Q_{reaction}}$	Heat liberated from 1 kmoles combustion of fuel	J/kg
$\mathbf{Q_{sonic}}$	Sonic heat transfer limit of thermosyphon	W
$\mathbf{Q_{thermosyphons}}$	Heat transfer by thermosyphons	W
$\mathbf{Q_{unaccounted}}$	Unaccounted heat transfer	W
$\mathbf{Q_{us}}$	Heat transfer crossing the upper surface of the fluidized bed	W
$\mathbf{Q_{viscous}}$	Viscous heat transfer limit of thermosyphon	W
$\mathbf{Q_{wall}}$	Heat transfer from the fluidized bed to the fluidizing column	W
$\mathbf{R_1}$	Thermal resistance between the fluidized bed and containing wall	K/W
$\mathbf{R_2}$	Thermal resistance of the fluidizing column	K/W
$\mathbf{R_4}$	Thermal resistance of the outer surface of the insulating material	K/W

$\mathbf{R_{4conv}}$	Convection component of thermal resistance of the outer surface of the insulating material	K/W
$\mathbf{R_{4rad}}$	Radiative component of thermal resistance of the outer surface of the insulating material	K/W
Ra	Raylaigh number for free convection between the outer surface of the insulating material and the atmosphere	K/W
$\mathbf{R_{air}}$	Gas constant of air =287.0	J/kg.K
$\mathbf{R_c}$	Total thermal resistance of the direct immersed coil	K/W
$\mathbf{R_{c1}}$	Thermal resistance between the inner surface of the direct immersed coil and the cooling fluid	K/W
$\mathbf{R_{c2}}$	Thermal resistance of the direct immersed coil thickness	K/W
$\mathbf{R_{c3}}$	Thermal resistance between the outer surface of the direct immersed coil and the bed	K/W
Re	Reynolds number at fluidization conditions	
$\mathbf{Re_l}$	Reynolds number of the liquid film inside the thermosyphon	
$\mathbf{Re_{mf}}$	Reynolds number at minimum fluidization $Re_{mf} = \left(\frac{\rho_g U_{mf} d_p}{\mu_g}\right)$	
$\mathbf{Re_v}$	Axial vapor Reynolds number inside the thermosyphon	
$\mathbf{Re_w}$	Reynolds number of the cooling fluid through the heat sink	
$\mathbf{R_t}$	Total Thermal Resistance Between The Bed And The Ambient	K/W
$\mathbf{T_a}$	Temperature of inlet fluidizing air	K
$\mathbf{T_{atm}}$	Atmospheric temperature	K
$\mathbf{T_{bed}}$	Fluidized Bed temperature	K
$\mathbf{T_{ci}}$	Temperature of the inside surface of the condenser of the thermosyphon	K
$\mathbf{T_{coolant\ in}}$	Temperature of the cooling fluid at inlet to the heat sink	K
$\mathbf{T_{coolant\ out}}$	Temperature of the cooling fluid at outlet from the heat sink	k
$\mathbf{T_{eo}}$	Temperature of evaporator external surface	K
$\mathbf{T_{film}}$	Temperature of the film layer at the outer surface of the insulating material	K
$\mathbf{T_{ins}}$	Temperature of the outer surface of the insulating material	K
$\mathbf{T_{is}}$	Temperature of the outer surface of the immersed surface in the fluidized bed	K
$\mathbf{T_p}$	Temperature of liquid pool inside the thermosyphon	K
$\mathbf{t_{packet}}$	Packets spending time at the surface of pipe in fluidized bed	s
$\mathbf{T_{ref}}$	Standard reference temperature = 298	K
$\mathbf{T_{sat}}$	Saturation Temperature of Working Fluid	K
$\mathbf{T_{sink}}$	Temperature of the heat sink	K
$\mathbf{T_v}$	Temperature of vapor inside the thermosyphon	K

T_{wi}	Temperature of the inner wall of the fluidizing column	K
$T_{wi,f}$	Temperature of the freeboard inner wall	K
t	time	s
t_s	Characteristic thermal time for a single solid particle at the surface of pipe in fluidized bed	s
U	Fluidizing velocity	m/s
U_b	Characteristics bubble velocity	m/s
U_k	Minimum velocity at which transition from bubbling to turbulent regimes	m/s
U_{mb}	Minimum bubbling velocity	m/s
U_{mf}	Minimum fluidization velocity	m/s
U_{ms}	Minimum slugging velocity	m/s
$U_{terminal}$	Terminal velocity of the fluidizing particles	
U_{tr}	Minimum vertical transport velocity	m/s
V_{cw}	Volume of cooling water displaced by cooling water flow meter	m^3
V_e	Evaporator volume of the thermosyphon	m^3
V_f	Volume of fuel displaced by fuel flow meter	m^3
V_t	Thermosyphon volume	m^3
z	Axial direction of bed centerline	
z_1	Thermal resistance of bed to evaporator external surface	K/W
z_{10}	Thermal axial resistance of the thermosyphon wall	K/W
z_2	Thermal resistance of the evaporator wall	K/W
z_3	Thermal resistance of evaporator film	K/W
z_{3f}	Thermal resistance of evaporating film	K/W
z_{3p}	Thermal resistance of nucleate boiling	K/W
z_4	Thermal resistance of vapor-liquid interface resistance at the evaporator	K/W
z_5	Thermal resistance of vapor pressure drop resistance	K/W
z_6	Thermal resistance of vapor-liquid interface resistance at the condenser	K/W
z_7	Thermal resistance of the condenser film	K/W
z_8	Thermal resistance of the condenser wall	K/W
z_9	Thermal resistance of sink to condenser external surface	K/W
z_a	Number of fluidizing air kmoles	kmoles
z_t	Equivalent total thermal resistance of thermosyphon	K/W

LIST OF GREEK AND SPECIAL SYMBOLS

Symbol	Definition	Unit
Δ_1	Thickness of the fluidizing column	m
Δ_2	Thickness of the insulating material	m
$\Delta h_{orifice}$	Manometer pressure difference across the orifice	m
$\Delta Pgas$	Pressure drop due to fluidizing gas weight	Pa
ΔP_{mf}	Pressure drop of minimally fluidized bed	Pa
$\Delta P_{particles}$	Pressure drop due to fluidized particles weight	Pa
ΔP_{wall}	Pressure drop due to friction at bed walls	Pa
ΔT_{hp}	Temperature difference across thermosyphon	K
ρ_{air}	Density of air upstream orifice	kg/m^3
ρ_{cw}	Cooling water density	kg/m^3
ρ_f	Fuel density	kg/m^3
ρ_{film}	Density of the film layer at the outer surface of the insulating material	kg/m^3
ρ_g	Density of fluidizing gas	kg/m^3
ρ_{Hg}	Density of mercury =13600.0	kg/m^3
ρ_l	Density of the liquid film	kg/m^3
ρ_p	Density of fluidizing particles	kg/m^3
ρ_v	Density of the vapor film	kg/m^3
λ_{bed}	Thermal conductivity of the container wall material	W/m.K
λ_{eff}	Effective thermal conductivity of the dense phase	W/m.K
λ_{film}	Thermal conductivity of the film layer at the outer surface of the insulating material	W/m.K
λ_g	Thermal conductivity of fluidizing gas	W/m.K
λ_{ins}	Thermal conductivity of the insulating material	W/m.K
λ_l	Thermal conductivity of the liquid film	W/m.K
λ_p	Thermal conductivity of fluidizing particles	W/m.K
λ_t	Thermal conductivity of the thermosyphon material	W/m.K
λ_w	Thermal conductivity of the cooling fluid	W/m.K
μ_{film}	Dynamic viscosity of the film layer at the outer surface of the insulating material	Pa.s
μ_g	Dynamic viscosity of fluidizing gas	Pa.s
μ_l	Dynamic viscosity of the liquid film	Pa.s
μ_v	Dynamic viscosity of the vapor film	Pa.s
μ_w	Dynamic viscosity of the cooling fluid	Pa.s
ε_b	Bubble voidage	

ε_{bed}	Emissivity of bed material	
ε_{eo}	Emmisivity of the evaporator external surface	
ε_{fw}	Emmisivity of the freeboard inner wall	
ε_{g}	Emmisivity of the fluidizing gas	
ε_{insatm}	Emmisivity of the outer surface of the insulating material	
ε_{is}	Emissivity of the outer immersed surface in the fluidized bed	
ε_{mf}	Bed voidage at minimum fluidization	
ε_{net}	Net emissivity of the bed	
ε_{o}	Static bed voidage	
ε_{ov}	Overall bed voidage	
ε_{p}	Emmisivity of fluidizing particles	
εwi	Emissivity of the inner Wall of Fluidizing Column	
σ_{w}	Surface tension of the working fluid	
σ	Stephan – Boltzmann constant for radiative heat transfer	$W/m2.K^4$
ξ	Dummy variable	
δ	Liquid film thickness inside the thermosyphon	m
τ_{δ}	Shear stress between a falling liquid film and a countercurrent vapor flow inside the thermosyphon	N/m^2
$\tau_{\delta}+$	Nondimensional liquid-vapor interfacial shear stress inside the thermosyphon	
νl	Kinematic viscosity of the liquid inside the thermosyphon	
Φp	Sphericity or shape factor of fluidized particles	
Φ	Viscosity dissipation term	

Abbreviations

HP-HE: Heat Pipe-Heat Exchanger
LPG: Liquefied Petroleum Gas
AFBC: Atmospheric fluidized bed combustor
PFBC: Pressurized fluidized bed combustor
CFBC: Circulating fluidized bed combustor
ACFBC: Atmospheric circulating fluidized bed combustor
PCFBC: Pressurized circulating fluidized bed combustor
TDF: Tire derived fuel
RDF: Refuse derived fuel
M.I.G.: Metal inert gas
H.T.L.R.: Heat Transfer Limit Ratio Defined as:
Heat Transfer by 1 Heat Pipe/Minimum Heat Transfer Limit of the Heat Pipe

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