ARTICLE IN PRESS

Energy Conversion and Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Heat transfer study on open heat exchangers used in jaggery production modules – Computational Fluid Dynamics simulation and field data assessment

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ARTICLE INFO

Article history:
Received 17 November 2015
Accepted 2 March 2016
Available online xxxx

Keywords:
Pans
Jaggery
Flue gases
Computational Fluid Dynamics
Nucleate boiling heat transfer

ABSTRACT

Jaggery (also called organic sugar) is a concentrated product of sugarcane juice that is produced in rural communities in the highlands and jungle of Peru. In the last few years there has been an increase in the exports of jaggery and higher volumes of production are required driving this activity from a rural process with small production to an industry seeking greater productivity. In this framework, optimization of the use of energy becomes essential for the proper development of the process of production and the correct performance of the involved equipment. Open heat exchangers made of stainless steel are used in the production of jaggery. These heat exchangers containing sugarcane juice are placed over a flue gas duct. The thermal energy contained in the gas is used to evaporate the water contained in the sugarcane juice thickening the juice and after evaporating almost all the water, a pasty crystalline yellow substance is left in the boiling pan which becomes solid after cooling, this is the jaggery.

The modeling and simulation of heat transfer between the combustion gases and the juice is very important in order to improve the thermal efficiency of the process. It permits to know with a high level of detail the physical phenomena of heat transfer occurring from bagasse combustion flue gases to sugarcane juice. This paper presents the results of the numerical simulation of heat transfer phenomena in the open heat exchangers and those results are compared to field measured data. Numerical results about temperature drop of flue gases in the several locations of the jaggery furnace are in good accordance with field measurements, validating the predictive capacity that Computational Fluid Dynamics model offers in the detailed representation of the fluid flow and heat transfer characteristics of such furnace, ensuring the design of future jaggery installations with higher thermal efficiency and sugarcane production.

1. Introduction

In the first years of the 2000 decade, a Peruvian non-governmental organization started the exportation of a kind of granulated organic sugar – also called jaggery – produced from sugar cane crops collected from more than 6000 farmers who depend of jaggery production and exportation to obtain incomes that permit to increase their level of material prosperity. Nowadays, the jaggery demand has increased to a degree that present production does not satisfy the requirements of the international markets. Therefore, it is necessary to increase its production by strengthening the initial stages of the agribusiness chain, that is to say, the expansion and improvement of sugar cane crops as well as of their harvesting and transport and, of course, of the production of jaggery.

The increase in the jaggery production can be achieved through the construction of new high capacity jaggery processing installations or by the modernization of the existing ones. Another fundamental aspect of the jaggery production process is fuel self-sufficiency, which means the amount of bagasse consumed during the jaggery production is less than the amount of wet bagasse produced during milling. Thus, jaggery installations are self-sufficient when there is no need to purchase more bagasse either to use other alternative fuels in the jaggery production. Significantly, fuel self-sufficiency helps to reduce the region deforestation and the greenhouse gases emissions.

Jaggery production modules consist of operational units where: (i) the sugar cane passes through a milling process in order to

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http://dx.doi.org/10.1016/j.enconman.2016.03.005
0196-8904/

Nomenclature

Latin characters

a_g	overall absorption coefficient of CO_2–H_2O mixture (1/m)
$a_{g,prod}$	overall absorption coefficient of flue gases (1/m)
$a_{\epsilon,i}$	weight factor of the *i*-th gray gas
$b_{\epsilon,ij}$	*j*-th polynomial coefficient of the *i*-th gray gas
c	speed of light (m/s)
$c_{p,i}$	constant pressure specific heat of *i*-th gas (kJ/kg K)
$c_{p,l}$	constant pressure specific heat of the liquid phase (kJ/kg K)
$c_{p,l}$	constant pressure specific heat of the vapor phase (kJ/kg K)
$c_{p,prod}$	constant pressure specific heat of flue gases (kJ/kg K)
C_{lim}	stress limiter coefficient
C_{sf}	a Roshenow constant
g_i	gravity acceleration vector (m/s^2)
G	incident radiation (W/m^2)
G_ω	production term of turbulent frequency
h	convection heat transfer coefficient (W/m^2 K)
h_{boil}	boiling convection heat transfer coefficient (W/m^2 K)
$\widehat{H}_t$	Favre averaged of total enthalpy (kJ/kg)
H_{lv}	enthalpy of vaporization (kJ/kg)
k_{inox}	thermal conductivity of stainless steel (W/m K)
k_{prod}	thermal conductivity of flue gases (W/m K)
k_l	thermal conductivity the liquid phase (kJ/kg K)
k_v	thermal conductivity the vapor phase (kJ/kg K)
I	radiation intensity (W/m^2 str)
I_t	turbulent intensity
k	turbulent kinetic energy (m^2/s^2)
l	characteristic length scale (m)
L_m	mean optical pathlength (m)
Ma	Mach number
p	static pressure (Pa)
p_g	partial pressure of all participant gases (atm)
p_{gauge}	gauge pressure (Pa)
P_κ	production term of turbulent kinetic energy
Pr	Prandtl number
Pr_l	Prandtl number of the liquid phase
q''_{boil}	boiling convective heat flux (W/m^2)
q''_c	wall convective heat flux (W/m^2)
q''_r	radiative heat flux vector (W/m^2)
q''_w	total wall heat flux (W/m^2)
s	a Roshenow exponent
$\widetilde{S}_{ij}$	Favre averaged stress tensor (Pa)
$\overline{S_r}$	averaged source term due to radiative heat transfer
T	temperature (K), (°C)
T_{boil}	water boiling temperature (K), (°C)
$T_{0,SC}$	sugar cane juice temperature contained in the semi-cylindrical pan
$T_{0,SEI}$	sugar cane juice temperature contained in the semispherical I pan
$T_{0,SEII}$	sugar cane juice temperature contained in the semispherical II pan
$T_{0,FPI}$	sugar cane juice temperature contained in the finned-plate I pan
$T_{0,FPII}$	sugar cane juice temperature contained in the finned-plate II pan
T_{in}	inlet temperature (K), (°C)
T_{sat}	saturation temperature (K), (°C)
T_w	wall temperature (K), (°C)
$\dot{V}_{in}$	inlet volumetric flow (m^3/s)
$\overline{W}_{inox}$	molar weight of stainless steel (kg/kmol)
$\overline{W}_{prod}$	molar weight of flue gases (kg/kmol)
u_i	instantaneous velocity vector (m/s)
u_{in}	inlet velocity (m/s)
$\tilde{u}_i$	Favre-averaged velocity vector (m/s)
u''_i	Favre fluctuating velocity vector (m/s)
x_i	position vector
Y_i	mass fraction of the *i*-th specie
$\tilde{Y}_i$	Favre-averaged mass fraction of the *i*-th specie
Y_κ	destruction term of turbulent kinetic energy
Y_ω	destruction of turbulent frequency

Greek characters

β^*	calibration parameter of the k–ω model
Γ	parameter of the P-1 radiation model
ε	turbulent dissipation rate (m^2/s^3)
ϵ_T	total emissivity of the participant mean
ϵ_w	wall emissivity
κ_i	pressure-dependent absorption coefficient (1/m atm)
μ	molecular viscosity (Pa s)
μ_l	molecular viscosity of the liquid phase (Pa s)
μ_v	molecular viscosity of the vapor phase (Pa s)
μ_{inox}	molecular viscosity of stainless steel (Pa s)
μ_{prod}	molecular viscosity of flue gases (Pa s)
μ_t	turbulent (eddy) viscosity (Pa s)
$\bar{\rho}$	Reynolds averaged density (kg/m^3)
ρ_l	density in the liquid phase (kg/m^3)
ρ_l	density in the vapor phase (kg/m^3)
ρ_{inox}	density of the stainless steel (kg/m^3)
ρ_{prod}	density of the flue gases (kg/m^3)
ρ_v	density in the vapor phase (kg/m^3)
σ_l	surface tension of the liquid (N/m)
σ_κ	Prandtl number of turbulent kinetic energy
σ_ω	Prandtl number and turbulent frequency
ω	turbulence frequency (1/s)
$\hat{\omega}$	corrected turbulence frequency (1/s)

extract their juice, (ii) by heating and evaporation, this sugar cane juice goes through a water extraction process with the purpose to obtain the syrup, the thermal energy necessary is produced in a furnace, (ii) this syrup is crystallized by mechanical agitation within a range of controlled temperature in order to get the jaggery as a final product.

For heating and evaporation processes, a jaggery production unit requires of a furnace which consists of a combustion chamber, a flue gas duct, a chimney and pans (see Fig. 1). The thermal energy is obtained from the combustion of residues from cane grinding, also called bagasse. The flue gases, which are obtained from the bagasse combustion, flow through the interior of the flue gas duct transferring thermal energy to the pans. These pans are open heat exchangers whose function is to evaporate water from the sugar cane juice until it becomes syrup. There are several types of pans, the type of pan used depends on the particular part of the process which the sugarcane juice is suffering, finned flat and pirotubulars pans are used by sugar cane juice clarification and evaporation processes, whereas semicylindrical and semispherical pans are used in the ultimate boiling phase of the sugar cane juice.

For an existing jaggery production unit, the increment of jaggery production as well as fuel self-sufficiency can be achieved by the upgrading of its furnace. One way this can be done is by the substitution of pans for others that are thermally more efficient. For this, it will be necessary a thorough heat transfer study of pans of different geometries to select that capable of transfering in a efficient way the flue gases thermal energy to the sugar cane juice.

Please cite this article in press as: La Madrid R et al. Heat transfer study on open heat exchangers used in jaggery production modules – Computational Fluid Dynamics simulation and field data assessment. Energy Convers Manage (2016), http://dx.doi.org/10.1016/j.enconman.2016.03.005