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Influence of flow regime and thermal power on residence time distribution in tubular Joule Effect Heaters

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ABSTRACT

To improve treatment homogeneity in tubular Joule Effect Heater (JEH), geometric modifications could be used even in laminar regime inducing flow perturbation and mixing.As a response variable, residence time distribution (RTD) is an important parameter and it has been commonly used in determining the performances of industrial heat exchangers.In present work, our objectives were (i) to investigate the impact of processing conditions (flow regime, heat flux) on RTD in an industrial JEH equipped with smooth and modified tubes, (ii) to contribute to the estimation of treatment homogeneity versus global energetic performances of heat exchanger and (iii) to validate a general reactor model.Analytical solution and systemic analysis of RTD signals were reported. The evolutions of mean reduced variance, β^2 against efficiency number, *Eff* for smooth ($\beta^2 = 0.00129 \cdot Eff - 0.0300$, $R^2 = 0.992$) and modified ($\beta^2 = 0.000547 \cdot Eff - 0.0169$, $R^2 = 0.979$) tubes exhibited a similar and linear relationship. Under the conditions investigated ($38 < Re < 10{,}000$, $4 < Pr < 950$ with Newtonian fluids), treatment homogeneity was significantly improved by modified geometry and strong interactions between heat transfer and hydrodynamics. A significant decrease in reduced variance under both laminar ($\beta^2_{ST} = 0.1054 \cdot Exp(-0.00518 \cdot P/(\rho \cdot Q))$, $\beta^2_{MT} = 0.0661 \cdot Exp(-0.00342 \cdot P/(\rho \cdot Q)))$ and turbulent ($\beta^2_{ST} = 0.00624 \cdot Exp(-0.00447 \cdot P/(\rho \cdot Q))$, $\beta^2_{MT} = 0.00108 \cdot Exp(-0.00195 \cdot P/(\rho \cdot Q)))$ regimes was observed versus heat energy.However geometric modification and heat treatment affected the residence time distribution and specifically reduced variance, β^2 within same order of magnitude.Systemic analysis of experimental data enabled to evaluate two reactor models:Dispersed Plug Flow (DPF) and Plug Flow (PF) + 2 Continuous Stirred Tank Reactor (CSTR) with and without convolution and with 1 or 2 degrees of freedom.Second model could be considered as the most accurate model to predict RTD in JEH with an accurate degree of confidence for residence time and reduced variance estimation ($\tau = 0.995 \cdot t_s$ $R^2 = 0.64$, error < 3% and $\beta^2 = 0.3119 \cdot \left(\beta^2_{\exp}\right)^{0.73}$ $R^2 = 0.98$) and a simplified model with only 1 degree of freedom can be used.

1. Introduction

In the food industry, heat treatment remains the oldest and the most frequently used process (heating, pasteurisation, sterilisation, cooking and cooling) and heat exchangers stand as fundamental equipment. In spite of great improvement in conventional technologies over the last few decades, heat treatment remains a complex operation (reduction of heat transfer coefficient, impact and kinetics of fouling mechanism, heat treatment homogeneity and flow pattern).

Enhancing the performance of heat exchangers is at the heart of improving exchanger efficiency and thus at the core of energy optimization of industrial process (Harion et al., 2000). Many studies are and were devoted to the increase of heat transfer and mixture/flow pattern modification in food process, implementing different technological option. Vashitsh et al. (2008) reported a review on the potential applications of curved geometries whose chaotic advection (impact of geometrical modification on flow pattern, heat transfer).

To improve treatment homogeneity in tubular Joule Effect Heater (JEH), geometric modifications could be used even in laminar regime inducing flow perturbation and mixing. As a response variable, residence time distribution (RTD) is an important parameter and it has been commonly used in determining the performance of industrial heat exchangers (Pinheiro Torres and Oliviera, 1998; Roetzel and Balzereit, 2000; Sancho and Rao, 1992). RTD analyse provides information about the degree of mixing, cooking and shearing which play an important role in the final product quality. RTD are used for scale-up and improving equipment design. RTD analyse provides information about the degree of mixing, cooking and shearing which play an important role in the final product

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Nomenclature

List of symbols

a, b, c, d	coefficient
C	concentration (mol/l)
Cp	specific heat (J/kg K^{-1})
Da	Darcy number (/)
D_{ax}	axial dispersion coefficient (m^2/s)
d_h	hydraulic diameter (m)
e	space (m)
E	RTD function (s^{-1}) or (/)
Eff	efficiency number (/)
F	cumulative RTD function (/)
G	Laplace transform of E
Gr	Grasshof number (/)
Gz	Graetz number (/)
j	Colburn number (/)
L	length (m)
n	exponents (/)
P	heat power (W)
Pe_L	Peclet number calculated with the pipe length (/)
Pr	Prandtl number (/)
Nu	Nusselt number (/)
Q	volume flow rate (m^3/s)
Re	Reynolds number (/)
s	skewness (s^3)
t	time (s)
t_S	mean residence time (s)
T	temperature (°C)
U	mean fluid velocity (m/s)
V	volume (m^3)
x, y	inlet and outlet normalised signals
z	axial direction (m)
X, Y	Laplace transform of x and y

Greek symbols

α	plug flow contribution (/)
ξ	geometrical factor (/)
β^2	reduced variance (/)
θ	reduced time (/)
ΔP	pressure drop (bar)
μ	viscosity (Pa s)
ρ	fluid density (kg/m^3)
σ^2	variance (s^2)
Γ^j	moment of order j (s^j)
Γ'	centred moment of order j (s^j)
τ	mean holding time (s)

Indices

CSTR	constant stirred tank reactor
exp	experimental
FC	forced convection
in	inlet
PF	plug flow
lam	laminar
m	modification
MC	mixed convection
out	outlet
tran	transitory
turb	turbulent

quality. RTD are used for scale-up and improving equipment design. However, RTD of real processes arise from a complex interaction between the velocity profile, diffusion, turbulence, heat transfer, etc. For the analysis of experimental results, the non-ideality of the tracer and its detectability must also be considered. RTD are often described on the basis of simple models, dispersed plug flow (DPF) or a cascade of N continuous stirred tank reactors (CSTR), whereby the fitting is not always good. The assumption under these models only roughly characterizes the real existing processes.

Harion et al. (2000) reports the mixing and heat transfer increase in a tube with alternate successive deformations. This geometry from a cylindrical tube, imposes on the fluid flow radial contractions and stretching keeping a constant (or quasi constant) section. The deformation based on alternate elliptic forms is a function of the ondulations amplitude, the streamwise wavelength and the direction of the principal axes of deformation. Their results lead to an efficiency factor (ratio between pressure drop and heat transfer coefficient increases) of about 1.2 for $Re < 3000$.

Castelain et al. (1997,2006) and Chagny et al. (2000) investigated the efficiency of chaotic advection regime in a twisted duct flow. A configuration representing a three dimensional steady open flow consisted of helical and chaotic mixers made of identical bends. Each bends consists of a 90° curve stainless-steel tube of circular cross section ($\emptyset_{int/ext}$ = 23/25 mm). The mean radius of curvature of the bends is 126.5 mm, which yields a mean curvature ratio of 0.18. Hydrodynamic (friction curve and residence time distribution) as well as heat transfer performances are reported and compared with Newtonian and non-Newtonian fluids. The results show that at low Reynolds numbers, heat transfer is higher and heating more homogeneous for chaotic advection flow, with no increase in energy expenditure. Overall heat transfer coefficient reaches a maximum at Reynolds number around 250. At high Reynolds numbers ($Re > 1000$), the configuration has no influence on heat transfer. The experimental evaluation of the residence time distribution with the use of a plug flow model with axial dispersion part exchanging mass with a stagnant region, has allowed the determination of an effective axial dispersion coefficient with two configurations in the case of pseudoplastic fluid and for $Re < 300$.

André et al. (2007) and Fillaudeau et al. (2001) investigated the impact of processing conditions on RTD in industrial JEH with smooth and modified tubes. A geometrical modification was selected in agreement with food applications considering pressure drop increase, heat transfer coefficient increase, propensity to fouling and cleaning efficiency (Lefebvre, 1998). This motive was validated with model and real product at industrial scale and patented. RTD with both geometries (smooth circular and modified tubes) on a complete industrial exchanger (L = 1.40 and 1.50 m, $\emptyset_{int/ext}$ = 18/20 and 23/25 mm) was studied versus flow regime ($80 < Re < 2000$) and a general reactor model was validated. The analysis demonstrates that (i) flow regime improve treatment homogeneity by increasing the plug flow contribution and reducing the value of reduced variance, (ii) the earliest transition from laminar to turbulent flow regimes (shifting in critical Reynolds number) due to geometrical modifications and nominal tube diameter induce a reduced variance decrease.

In present work, our objectives were (i) to investigate the impact of processing conditions (flow regime, heat flux) on RTD in an industrial Joule Effect Heater (JEH) equipped with smooth and modified tubes (L = 1.40 m, $\emptyset_{int/ext}$ = 18/20 mm), (ii) to validate a general reactor model and (iii) to contribute to estimate treatment homogeneity versus flow and heating conditions. RTD is investigated following the methodology described by Thereska (1998). In a first step, analytic solution of RTD signals are reported and dis-