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FLOW CHARACTERISTIC AND PRESSURE DROP INSIDE THE HORIZONTAL SCRAPED SURFACE HEAT EXCHANGER

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ABSTRACT

Thermal processing (heating, cooling, crystallization) of high viscous or sticky products, usually containing particles or alter state when thermally processed are managed in chemical, food and consumption industry by scraped surface heat exchangers. These products are in most of the time non-Newtonian and sensitive products. Because of intensive presence of fouling and low heat transfer coefficient the rotating shaft (usually speaking of votator type of scraped surface heat exchangers) is equipped with scraper blades to keep clean the heat transfer surface and to mix the product as much as possible from the heat transfer surface into the main axial flow. Often, at the entrance of the product from the inlet cell to the main cylindrical heat exchanger part, a specific static mixers, homogenizers are applied (at outlet as well, but for different purpose – make additional mixing after thermal processing of the product). At inlet side the mixers are applied to flatten the velocity profile which is beneficial for the heat exchange process. The presented paper deal with the type of static mixers at the entrance and outlet from the point of view how the velocity profiles looks like and what is the effect on the pressure drop through them. The results show that the usage of different type of the mixers have no significant effect on the velocity profile when product is already managed by rotating scrapers. On the other hand it has quite significant impact on the pressure drop, what can lead to the higher energy consumption.

Keywords: Scraped surface heat exchanger, velocity profile, pressure drop, character of flow

1. INTRODUCTION

Thermal treatment (heating, cooling, crystallization) of high viscous, in most of the time non-Newtonian products in chemical, food and consumption industry (e.g. caramel, puddings, chocolate, cheese, deboned meat, oils, glues, resins, printing ink, ice creams etc.) are handled by scraped surface heat exchangers (SSHE). These heat exchangers are usually votator type, where rotating shaft inside the heat transfer tube is arranged by scrapers and sometimes with additional rectifiers. By scrapers the heat transfer surface is managed to keep clean from fouling, which has one of the major impact on the heat transfer process. Secondary request of the scraper blades construction is to mix the product from the heat transfer wall into the main axial (usually laminar) flow. There are huge amount of executions of these constructions, called as mutator (rotating shaft with scraper blades and possible rectifiers on it). It

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should be mentioned that usage of certain construction can be more efficient for one type of product as for others. Things, having effect on usage of certain type of construction can be like the viscosity (in general the thermo-physical properties) of the treated product, sensitivity, economical approach, clean-ability (self-clean-ability), etc. In many cases there are used static, built in mixers to flatten the velocity profile directly at the inlet to the "process" area from the inlet cell and another at the outlet from the heat exchanger to allow the proper mixture of the product and keep the average overall temperature at the outlet. Both can have an advantages and disadvantages. By flattening the velocity profile we can reach a better heat transfer conditions, but getting higher pressure drop through the SSHE.

In this paper are presented some results from the more complex research work of experimental and numerical examination of horizontal scraped surface heat exchanger with one of the newly proposed internal construction –mutator. As a first step, the experimental measurements were done by the newly proposed mutator construction and compared with their numerical solutions, including the formation of correlations for Nu number calculation. Those results are presented in different paper [1]. The results showed a very good coincidence, even the simplified numerical model (area between the heat transfer tube, wall and the shaft) was applied at the numerical solution. As the continuity of research, numerous numerical analyses were done with more newly proposed mutators, different products with non-Newtonian behavior, and check some types of static mixers used at inlet and outlet, as their competence for different products. Hereby shown results from numerical analyses for 8 variations of usage of static mixers at inlet and outlet for honey and water as thermally treated product.

2. DEVELOPMENT AND PROGRESS IN RESEARCH

There are voluminous research works done in this field, usually experimental measurements to get correlation for calculation of Nu number. By development of computer technics and mathematical codes for CFD (computational fluid dynamic), more works are provided already by them (e.g. CFX, Fluent as Ansys products). From early results are well know the works of Huggins F. E. [2], who observed that using the scraper blades, causes higher efficiency of heat transfer. The difference was less notable for low viscous fluids as for the fluids, products with significant viscosity. In a case of crystallization, when crystallization occurred at the heat transfer wall the heat transfer coefficient value was estimated about 200-1000 $Wm^{-2}K^{-1}$, while it occurred in a near area of the heat transfer wall, the heat transfer coefficient was reported about 1000-2000 $Wm^{-2}K^{-1}$. Lattinen G. A. [3] was working on the theoretical solution for the inner side of the heat transfer wall based on the heat conduction for the semi-infinite body. He presumed the cooling on the heat transfer wall by molecular transport until the product is not mixed with the main flow by scrapers. His correlation has the form:

$$Nu = \left(\frac{2}{\sqrt{2}}\right)(Re_{rot}PrZ)^{1/2}, \quad (1)$$

Härröd M. [4], [5] investigated about the character and profile of flow, radial and axial mixing as the heat transfer in a wide range of process conditions with water and starch pastes. The investigation was done quite detailed about the transition between laminar and vortical flow, their effect on radial mixing and radial temperature differences. Boccardi G. et al. [6] presented correlations prepared by dimensional analysis method for ice cream production. One of the correlation presented is in a form:

$$Nu = h_{iad}\frac{D}{k} = 0.208\left(\frac{\rho v D}{\mu}\right)^{0.7192}\left(\frac{c_p\mu}{k}\right)^{0.783}\left(\frac{ND}{v}\right)^{0.406}\left(\frac{D}{L}\right)^{0.523}, \quad (2)$$

Tero T. [7] in his dissertation thesis investigated with crystallization, especially with generation of crystals, their growth and their layer growth. Based on his investigation he reported a graph for heat transfer coefficient (inner and overall) and heat flow (specific heat flow) in dependence on flow speed for both. Pyle et al. [8] in their work focused on the mathematical model to understand and describe the blade wear and present forces at blade tips including the consideration of fluid flow in corners and edges. The blade construction has an impact on blade wear, which is important from the point of possible excess of fouling on the heat transfer wall and significant blade fragments in the processed product. Based on their model they reported the initial rapid wear which goes to zero rate by time. Fitt et al. [9] investigated about the theoretical model for Newtonian fluids inside the cylindrical annulus with scraping blades and their configurations. The investigation was done for channeling, which is one of the undesired effects inside the SSHE. Fluid, product flow through SSHE without real heat treating. Qin et al. [10] provided in their work a measurement on laboratory scraped surface heat exchanger to discover the heat transfer coefficient and power consumtion for freezing of 10wt.% sugar They presented a higher heat transfer coefficinet at phase change as without. Aloui F., Rehimi F., Dumont E., Legrand J. [11] presented an inverse method to determine the wall shear rate in SSHE using polarography technique. For experimental measurements they have used an industrial SSHE with high viscous of an isotherm Newtonian or non-Newtonian product, fluid (Emkarox HV45, polyethylene glycol (PEG) 35000 and shear-thinning guar gum). Pascual M. R., Ravelet F., Delfos F., Derksen J. J. and Witkamp G. J. [12] performed large eddy simulations of the turbulent flow, at the Reynolds number of $5x10^4$ for crystallizer geometry with main focus of the bottom region where the heat exchange surface was located. The simulation they validated by Stereoscopic Particle Image Velocimetry (PIV) experiments. Blel W., Legentilhomme P., Benezech T., Fayolle F. [13] investigated about clean-ability of inlet cell of the SSHE for optimization in order to reduce the hydrodynamically dead zones. The main focus was done on new extended correlation previously presented on a simple system between the wall velocity gradient and the clean-ability. They have tested for contamination by spore-forming bacteria and biofilm. Using pulsating flow was reported as increasing the fluctuations and thereby reduces the residual contamination. Yataghene M. and Legrand J. [14] prepared a detailed 3D CFD model and analyses for their own geometrical solution. As a CFD tool was used Fluent 6.3 and for mesh model Gambit 2.2.3 The analyses were run for

Newtonian fluid as pure Glycerin, for non-Newtonian fluid as 2 wt.% Carboxymethyl cellulose (CMC) and 0.2 wt.% Carbopol. Results, like temperature profiles are presented by several graphs. By increasing the rotating velocity in a case of non-Newtonian fluids the heat transfer was improved, while for pure Glycerin dramatically decreased. It was observed that viscous heating increases with rotating velocity. Nikolajev L N. [15] presented his correlation obtained by dimensional analyses in a form:

$$Nu = c_1 Re_{ax}^{e_1} Pr^{e_2} \left(\frac{ND_s}{v}\right) \left(\frac{Pr_f}{Pr_w}\right)^{e_4} \left(\frac{B}{D}\right)^{e_5} \left(\frac{L}{D}\right)^{e_6} \left(\frac{b}{D}\right)^{e^7} \left(\frac{d}{D}\right)^{e_8}, \quad (3)$$

Despite of available correlations and different results from already done research works, in a case of new design of SSHE's or new product which should be thermally processed a special care to be considered to avoid that used information would lead to wrong estimations about the sizing of SSHE or setting up the operational conditions of technological process. Detailed investigation should be done as well, to avoid dead zones inside the SSHE whcih can lead to the loss of quality of sensitive products during their thermal treatment.

3. LABORATORY UNIT & NUMERICAL MODEL OF NEW VOTATOR INCL. STATIC MIXERS

On Fig.1. can be seen the initical CAD design of the horizontal SSHE with the newly designed mutator construction built in. This unit was used for experimental measurement and the samplified model for numerical analysis. There are seen the position of static mixers (one of the type which is checked by following numerical analysis) at the inlet and outlet. On Fig.2. are shown the numerical models in 8 different variations, which were used for numerical analysis. There are 4 types of static mixers in 8 combinations. The first is a FREE type, which mean that no mixer is applied.The MIX type is a perforate plate with holes of 5 mm diameter. The ROT and COUNT mixers are homogenizing, „turbine" shape static mixers. The intention of numerical analysis is to discover the flow pattern and flow characteristic coused by these built in mixers and see the effect on heat transfer process. All combination can have its advantages and disadvantages, depend on thermally processed product, hereby checked for honey and water. Turbulent model was used SST with initial 5% of turbulency (proposed in a case of unknown turbulency at the beginning).

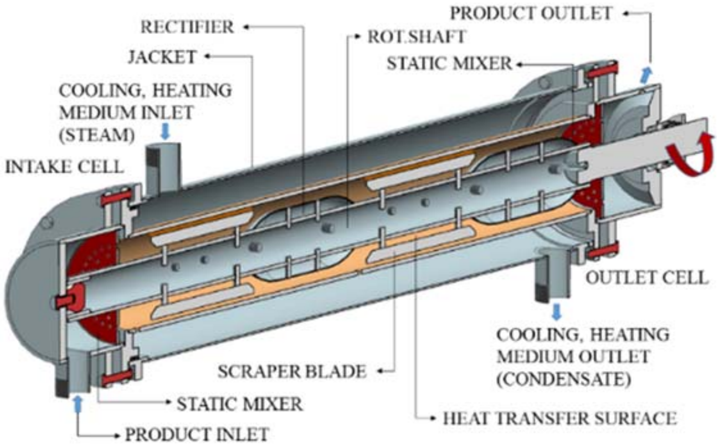

Fig. 1. Vertical cross section at center line through the horizontal SSHE, $D_{jacket-in}$=172 mm, $D_{heat-transfer-in}$=98.8/122.9 mm, $d_{shaft-out}$=48/60 mm

Process conditions as follows: Honey, inlet temperature 25°C, constant temperature of the heat transfer wall (prediction) 70°C, massflow m=1000kg/h and rotational velocity rpm=90 1/min. Water inlet temperature 30°C, constant temperature of the heat transfer wall (prediction) 95°C, massflow m=1000kg/h and rotational velocity rpm=90 1/min.The observation of pressure drops as on the Fig.3 and the overall temperature rise through the SSHE. Basically the Δp1 and Δp3 are the pressure drops on the built in statis mixers (rectifiers). Δp4 is the overall pressure drop, while Δp2 is the pressure drop inside-through the heat exchanger, cylindrical annulus “part“.

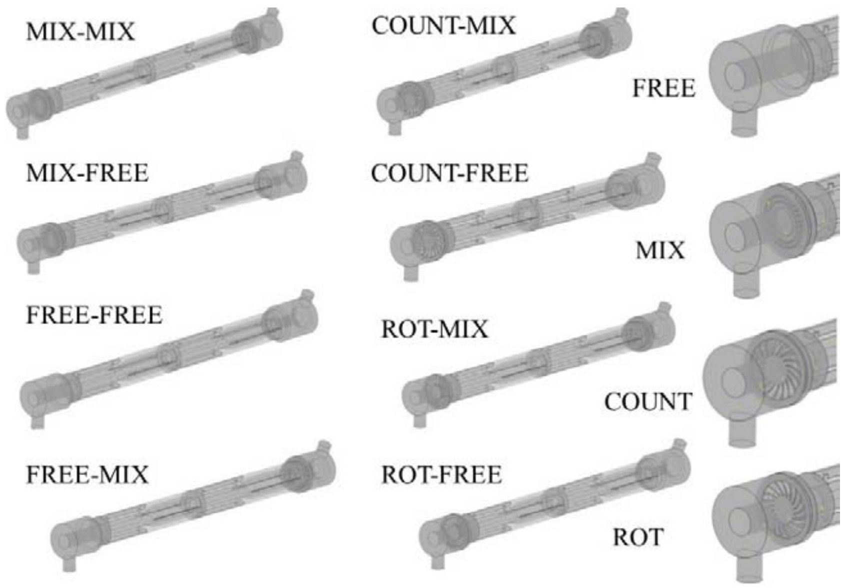

Fig. 2. variations of used static mixers and their positions for numerical analysis

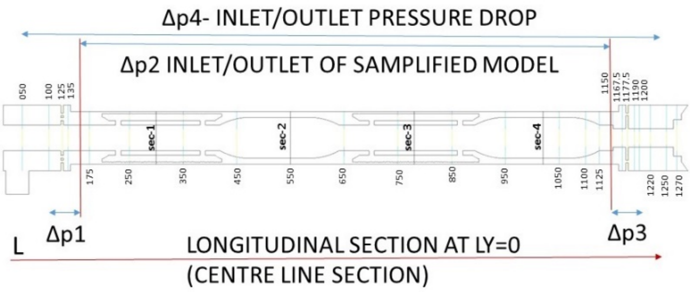

Fig. 3. Δp1-4 checked pressure drops between positions as marked

4. RESULTS

Hereby below are some results shown in the chart (Table 1.), from which can be see that static mixers has no real impact on pressure drop in a case of low viscous products like water, but it is significant when high viscous products are involved (now honey). The worst case is when perforated plate applied on both inlet, outlet position. When ROT or COUNT type of mixers used, the pressure drop is considerable less, while no mixers involved it is the lowest (what was predictable of course, and confirmed). In Table 2. is shown the temperature rise for all variations in a case of honey and for two variations in a case of water.

Table 1. Observed pressure drops according Fig. 3.

VARIATION	MIX-MIX	MIX-FREE	FREE-FREE	FREE-MIX	ROT-MIX	ROT-FREE	COUNT-MIX	COUNT-FREE	MIX-MIX	ROT-MIX
L [mm]	P [kPa]	P [kPa]	P [kPa]	P [kPa]	P [kPa]	P [kPa]	P [kPa]	P [kPa]	P [kPa]	P [kPa]
INLET	116,5	112,6	105,1	109,0	109,3	105,5	109,3	105,5	101,5	101,5
OUTLET	101,3	101,3	101,3	101,3	101,3	101,3	101,3	101,3	101,3	101,3
Δp2	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4	0,0	0,0
Δp4	15,1	11,3	3,8	7,7	8,0	4,2	8,0	4,1	0,2	0,2
Δp1	7,6	7,6	0,1	0,1	0,5	0,5	0,4	0,4	0,1	0,0
Δp3	3,9	0,0	0,0	3,9	3,9	0,0	3,9	0,0	0,1	0,1

Table 2. Temperature rise through horizontal SSHE according Fig. 2.

VARIATION	MIX-MIX	MIX-FREE	FREE-FREE	FREE-MIX	ROT-MIX	ROT-FREE	COUNT-MIX	COUNT-FREE
HEATING ΔT [°C]-H	9,00	9,30	9,30	9,00	9,00	9,30	9,00	9,30
HEATING ΔT [°C]-W	26,10				22,90			

H – honey; W - water

On Fig. 4. are shown 3D velocity profiles for two cases, MIX and COUNT type of mixers at inlet position. It's clearly seen that the axial velocity component (profile) which value is rapidly increased through the inserted mixers, is eliminated from the beginning after the inlet through the mixers by rotating scrapers. It was discovered that backflow can occur depend on the rotational velocity directly at the entrance to the cylindrical annulus area, caused by the rotating blades and in some other local areas. The intensity of the backflow at the entrance will cause the rapid temperature rise, which should be managed to avoid quality loss of the treated product. There are some possibility to reduce this effect by construction variation of mutators. It will be a future investigation which changes are advised to reduce the effect of backflow and optimize the rotational velocity.to reach the highest efficiency of heat exchange process but keep the backflow effect as less as possible.

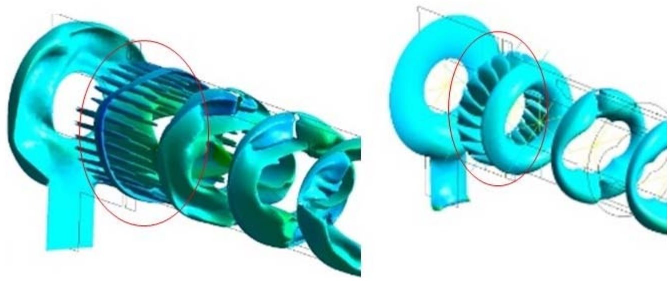

Fig. 4. visualisation of 3D velocity profile of axial (u) component of the velocity

5. CONCLUSION

From the results can be concluded that the usage of statis mixers need very special care depend on the material properties of the thermally trated product. For honey at given technological conditions is well seen that the temeparature rise for all variations has no difference, but pressure drop difference is significant. This mean some additional necessary power need to be inserted when static mixers are invloved. For low viscous products, like seen from the water the temperature rise is different, which can be explained by better mixing inside the SSHE (higher intensity of the turbulence present). On the other hand, as these kind of heat exchangers are commonly used for high viscous, mainly non-Newtonian products, the approach with honey gives more valuable results. (information from analyses made by water can be used for checking the possible cleaning process as well).The prediction that inlet velocity profile shouldbe maintained by static mixers, was not confirmed by these analysis.Another disadvantages for statis mixers, not considered in this work when products containing particles. In this case the size of „free-passage" should be properly checked to avoid quick fouling on mixers or blocking the flow of those particles. As additional disadvantage of static mixers can the their necessary cleaning frequency. The static mixers at outlet to insure the average temperature of the treated product is discutable as well. It will bring the benefit to make the final mixture of the product before leaving the heat exchanger and assure the good average temperature, but it will bring high pressure drop, which mean higher energy consumption. The usage of it can be affected by the product properties as well.

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