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(ICEMAEP'18)

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Title : **NUMERICAL ANALYSIS OF FLOW PATTERNS AND SHEAR RATES IN A SCRAPED SURFACE HEAT EXCHANGER**

Authors: **Malika Hallali, Abdekader Debab, Khalida Bekrentchir, Mallika Khalladi**

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April 29-30,2018
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CIEMEAP'2018

Fourth International Conference on

ENERGY, MATERIALS, APPLIED ENERGETICS AND POLLUTION

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April 29-30, 2018, Constantine, Algeria

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PREFACE

It gives us great pleasure to welcome all participants of the fourth international conference on Energy, Materials, Applied Energetics and Pollution (ICEMEAP2018) in Constantine.

To ensure their economic success all countries in the world must make a good energy management (produce energy at a lower cost) and simultaneously manage air, water and soil pollution (minimize releases). Indeed air pollution by certain gases from combustion (eg CO_2, CH_4, NO_x, etc….) cause the greenhouse effect (global warming) and has a detrimental effect on human health and the health of wildlife and flora, while chemical discharges into rivers or lakes in the nearby of factories cause pollution of groundwater. Also, the release of chemicals into the ground causes progressive soil sterility and thus threatens the food security in the world. These are the reasons for the increase in the number of research works undertaken in this field throughout the world in general and throughout our research centers and universities in particular.

Besides the topics of Energy and Pollution, the conference has also focused strongly on many areas of applied energetics(heat transfer enhancement techniques, fluid-structure interactions, turbomachinery, rheology, etc…) and materials research : synthesis, processing and properties. Many classes of materials were covered, either alone or in combination as composites: ceramics, metals, polymers, organic and inorganic materials.

The main purpose of this conference is to present the results of the research in these four topics by doctoral students, researchers and faculty members. The conference is also a great opportunity for the participants to exchange ideas, strenghten cooperation and to establish new contacts. Here is some information on the conference : We received over 750 proposals, under a third of these were retained after screening by the international reviewing committee. The selected papers were presented by Algerian and foreign scholars and many experts in the four conference topics were invited in order to raise the level of the conference by their debates with the presenters. The conference also allowed participants from the socio-economic sector to learn about the latest developments in the above topics in general and in the subtopics which have a big impact on Algerian economy in particular : renewable energies, new techniques of heat transfer enhancement and the techniques of detection and prevention of air, soil and water pollution.

Finally the Organizing Committee wishes to acknowledge the financial sponsorship of the conference by the **DGRSDT**(Direction Générale de la Recherche Scientifique et du Développement Technologique), the **ATRST**(Agence thématique de Recherche en Sciences et Technologie), the following five companies : **Biogalenic**, **Aigle**, **Sonelgaz**, **Tidjelabine Steel**, **Tidjelabine Briqueterie** and **MADI Laboratory**. Sincere thanks and appreciation go as well to the reviewers, the plenary session speakers and session chairs who undoubtedly contributed to the success of the conference. We also thank the officials of our university(the university Rector, the Vice Rector for external relations and the Vice Rector for postgraduate studies and research) and those of our faculty (Dean and Vice Dean of postgraduate studies and research) for the interest given to the conference and for having facilitated our preparation for this conference.

Professor M. KADJA

Conference Chairman

ICEMAEP'18

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NUMERICAL ANALYSIS OF FLOW PATTERNS AND SHEAR RATES IN A SCRAPED SURFACE HEAT EXCHANGER

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ABSTRACT

A numerical investigation of a scraped surface heat exchanger (SSHE) was undertaken, using the commercial CFD code FLUENT in order to characterize flow patterns and the shear rates. Regarding the operating conditions of the heat exchanger, Newtonian fluids and various geometric configurations were considered. A three-dimensional resolution of the continuity and momentum equations was conducted. After validation of the numerical strategy, a parametric study is made to better understanding the interactions between axial and rotation velocity. The simulation is achieved for various values of Taylor number for extended interval [0.09, 561.70] and axial Reynolds included [12, 2232]. Furthermore, the developed model has established the impact of the rotational speed and the mass flow rate on the shear rate.

Key Words: *Scraped Surface Heat Exchanger, Taylor number, Reynolds number, Newtonian fluid, Shear rate.*

NOMENCLATURE

Symbols :

A	follow area, m^2
D_h	hydraulic diameter ($D_h = D_t - D_r$
e	width of annular space($e=R_t-R_r$
L	tube length, m
l	element tube length, m
N	rotational velocity, tr.s^{-1}
n	flow behavior index of the fluid
n_L	blades number of tube
Q_m	mass flow rate, kg.s^{-1}
Q_V	volumetric flow rate, m^3.s^{-1}
Re_a	axial Reynolds number
Re_r	rotational Reynolds number
R_r	rotor radius, m
r	distance in the rotation axis, m
r^*	dimensionless radial position
Rt	outside cylinder radius of the
S_{max}	maximum shearing rate in
S_{moy}	average shearing rate in the
Ta	Taylor number
v_m	average flow velocity, m.s^{-1}
V_z	axial velocity, m.s^{-1}
V^*_r	dimensionless radial velocity
V^*_z	dimensionless axial velocity
V^*_θ	dimensionless rotational
X	radial position, m
Z	axial position, m
Z^*	dimensionless axial position
Z/e	dimensionless axial position

Greek letters:

δ	gap between blade and tube,
$\dot{\gamma}$	shear rate, s^{-1}
η	fluid dynamic viscosity, kg.m^{-1} s^{-1}
μ	fluid cinematic viscosity, m^2.s^{-1}
ρ	fluid density, kgm^{-3}
τ	stress shearing, N.m^2
Ω	rotating speed of the rotor, rad. s^{-1}

1. INTRODUCTION

The recent studies have been often focused on the analysis of the scraped surface heat exchange in agro alimentary industries. However, only one part results of these works are related to the oil industry, particularly products containing viscous paraffin. In this area, where the operation is based on the deparaffining, we noted that the oil tends to crystallize at ambient temperature. In order to remediate this latter, a suitable mechanical treatment has to be predicted with periodic stoppages of the installation in operation. The description of flows in SSHE was initiated by the works of Trommelen and Beek [1]. Indeed, it has been characterized by the superposition of a rotational velocity (Couette-type) caused by the rotation of the inner cylinder and axial velocity (Poiseuille-type). These flows are highly complex**,** while many theoretical studies have been conducted on SSHE in order to understand as deeply as possible the phenomena that occur and their impact on hydrodynamics, heat transfer, energy flows and distribution of residence time [2,3,4].

Numerical studies of Newtonian flow in three-dimensional systems are still out of reach for most industrial applications. It is not surprising that existing numerical results are largely limited to two-dimensional simplified flows where the axial flow effects are neglected, although the axial and the tangential flow are coupled because of their dependency on the shear rate. It is important to understand the consequences of the interaction of axial flow and tangential flows and their impact on the energy required for pumping Newtonian fluid. Many results predicting the velocity profile and the relationship between the axial mass flow rate and the shear rate were shown in the literature. Sun et al. [5] showed an independence of the tangential flow from the axial flow for Newtonian flow developed in the axial direction, although the reverse is not true.

Many different studies in this area have been investigated in order to determine models representing the flow behavior in SSHEs such as works of Härröd [3] and Naimi[4]. The latter showed that the progressive increase of rotating speed generates hydrodynamic instabilities known as Taylor instabilities: near a critical value of Taylor number, the flow changes from pure laminar to vortex, wavy vortex, and helicoids vortex flow up to turbulence regime. Härröd [3] indicated that the transition between laminar and vortex regime is very hard to predict accurately in SSHEs with visual methods. Dumont et al.[6] confirmed that the transition between laminar and vortex flow regime is not really defined. They determined a value of generalized Taylor number, using visualization methods, when vortices appear around $Tag \approx 80$ [7]. Moreover, Dumont et al. [8]were used an electrochemical method to measure the wall shear rate in a scaled-down model of SSHE with highly viscous solutions where two flow regimes were investigated: laminar and vortex flow. They revealed that high wall shear rate occurred at the scraped exchange surface, where this last one is 10–100 times higher than in an annulus space. Later they showed that the high increasing in shear rate was observed when electrochemical microelectrodes were scraped by the blades. In addition, all models proposed in many works such as Härröd [3] Naimi[4], Leuliet et al. [9] and Maingonnat et al. [10] have been devoted to estimate a global wall shear rate in the heat exchanger. The one, proposed by Trommelen and Beek [1] can predict high wall shear conditions in an SSHE, when the space between the blade edge and the outer wall surface is equal to few micrometers.

In the present work, we have simulated the flow models in scraped surface heat exchanger in three-dimensional geometry using the commercial code FLUENT. The evaluations of this numerical approach have been established by comparison with experimental results available in the literature. Also for Newtonian fluids in different geometric conditions, the effect of axial flow on hydrodynamic is determined by characterization of the flow and the flow transition, Taylor vortices and flow under the influence of blade motion in SSHE. In the other hand, we have quantified the mechanical treatment received by the product in order to complete the knowledge of shear conditions.

2. EQUIPMENT DESCRIPTION AND METHODOLOGY

2.1 Equipment description

The Schiller is a block of exchanger for cooling the mixture (solvent + paraffin oil). This equipment comprises twelve coaxial tubes connected in rows and equipped with a blade system. The total heat exchange surface of the cooler is 81.3 m^2. The scraper blades are in stainless steel fixed by springs on drive shaft. This facility provides a favorable stirring to crystal growth and prevents the accumulation of the paraffin on the exchanger walls. By the same way, the drive shafts of the scraper system are interconnected by a chain entrained by an electric motor (Figure 1).

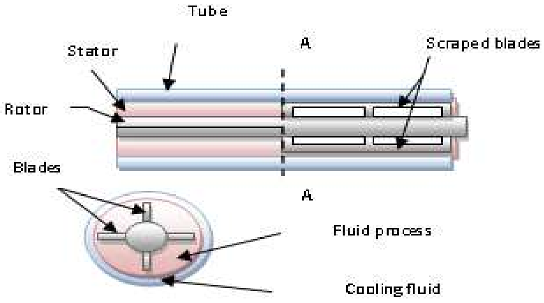


Figure 1. The schematic of the SSHE

The numerical tests were performed on the industrial scraped surface heat exchanger of an Algerian Refinery Company. It consists of two coaxial cylinders whose the inner is in rotation movement. The schilling process was accomplished by pumping of the mixture (deparaffined oil + solvents) through the jacket. The cooling occurs near the stator and blades scrape continuously the cooled working fluid (paraffinic oil+ solvent). With relation to geometrical dimensions, two different sizes were used from which the values are given in Table 1. For more details, we distinguished the length of the first with 1.08 m. It is equipped of the four blades with different spaces between the blade and the stator. They were taken equal to 0.13 mm, 1 mm, 1.5 mm and 2 mm respectively. The length of the second is 14.04 m with 52 blades.

D_t	0.153
D_r	0.102
D_r/D_t	0.6
L	14.04
Number of blade n_L	52
l	1.08
Number of blade n_l	4
Angle of blade	90°

Table 1. Geometrical data of the SSHE pattern

2.2 The fluids properties

In the present work, the computations are based on physical properties fluid provided by the technical department of the Algerian refinery in Arzew area. We assume that the density ρ, the thermal conductivity λ and the specific heat of the fluid Cp are practically temperature independent and that there is no phase change during this treatment. Two Newtonian fluids are used, a mixture of (paraffin oil + methyl ethyl ketone) and the Emkarok HV45 (35%), whose individual physical properties are shown in the following table:

Fluids properties	Oil + solvent	HV45 (35%)
Density (Kg/m^3)	841.33	1073
Viscosity (Pa.s)	0.173	0.43

Table 2. Physical properties of fluids in the process

2.3 Description of numerical method

Both geometries are three-dimensionally presented and meshed with hexahedral elementary volumes using the GAMBIT software (Fluent Inc.). Computational domain and Meshes topologies are shown in Figure 2. In order to ensure the goodness of results, we opted for very fine mesh, particularly at the end of the blades. We note that this approach of meshes distribution leads to identify areas where the heat exchange intensity is greater. The mesh cells were varied from coarse to fine size. The mid-fine mesh having 302300 nodes (310000 elements) and 650900 nodes (990000 elements) were found to show satisfactory results; hence chosen for further simulation for the both geometry. As we concerned about the turbulence and shear rate near the blade tip, so the velocity v and the shear rate are determined on an axial line drawn in front of the blade tip. While doing this study, we kept attention on the meshing near the wall instead of bulk domain as the study was related to wall measurements. Refining bulk domain increases the number of cells which is very difficult for computation work. High resolution scheme is both accurate and bounded. It is a second order scheme but also reduces to first order near discontinuities and in the free stream where the solution has little variation. The convergence criteria used to terminate the simulations was kept at 1×10^{-4} for all the parameters.

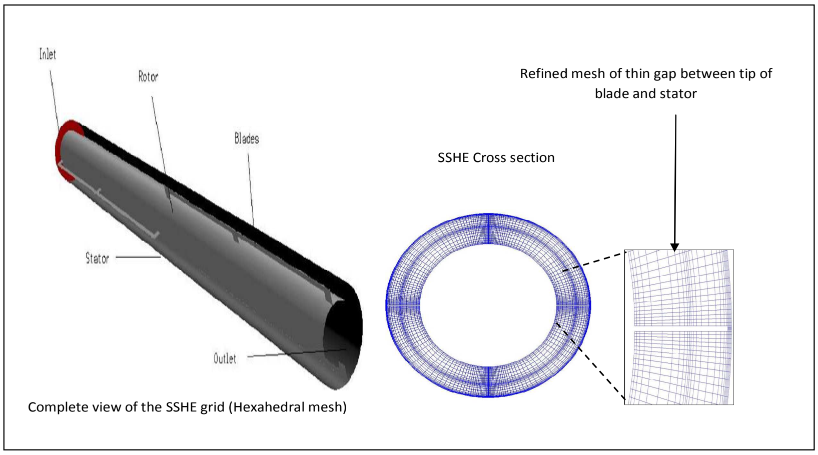


Figure 2. Computational domain and Meshes topologies

The velocity boundary conditions were set as:

- Boundary condition I: The tube velocity: $V=0$.
- Boundary condition II: The rotor and blade velocity: $V=\Omega.r$.

With the rotating movement, various modes of instability appear. For an imposed axial flow, the Taylor vortices appear for high rotation velocity values. However, the transition between the different regimes can be characterized by the Taylor number, axial and rotation Reynolds numbers. In the case of Newtonian fluids, the Taylor number is defined by the following relation:

$$Ta = \sqrt{\frac{R_t - R_r}{R_r}}\frac{\rho D_h}{2}\frac{\Omega R_r}{\eta} \qquad (1)$$

Where: Ω is the scraping velocity.

For our SSHE pattern, the Taylor number range available depends on the mixture composition and the rotation velocity. As an indication, a Taylor number 0 <Ta <600 corresponds to a rotation speed less than 10 rps. The transition between laminar and turbulent regimes occurs when Ta ≈ 80 according to Dumont [6]. Ta_c results. The axial Reynolds number is described by:

$$Re_a = \frac{V_z D_a^{1/2}}{\eta} \qquad (2)$$

Where v_m is the average flow velocity

Similarly, the rotational Reynolds number is given by:

$$Re_r = \frac{\rho \Omega D_r^2}{\eta} \qquad (3)$$

3. RESULTS AND DISCUSSIONS

3.1 Validation

To benchmark our computational results, we have used the data obtained from Yataghène's studies [11] where the particle image velocimetry (PIV) techniques have been performed to build the velocities profile. The comparison was made for a Newtonian fluid (pure glycerin η = 1.31 Pa.s, ρ = 1260 kg/m^3) in the following case: N = 3 rps, Qv = 1.38 10^{-5}m^3/s. The numerical results of our calculations of the velocity components(tangential, axial and radial) were compared with Yataghène experimental results, for an angular position of 90° and a relative axial position Z*=0.2, these results are depicted in Figure 3. The velocity components (axial and radial position) are dimensionless according to the following relationships:

$$V_z^* = v_z / v_m \qquad (4)$$

Where v_m is the average velocity of flow through the annular section.

$$V_r^* = v_r / (\Omega . R_r) \quad \text{et} \quad V_\theta^* = v_\theta / (\Omega . R_r) \qquad (5)$$

$$r^* = (r - R_r)/(R_t - R_r) \quad \text{et} \quad z^* = Z / lt \qquad (6)$$

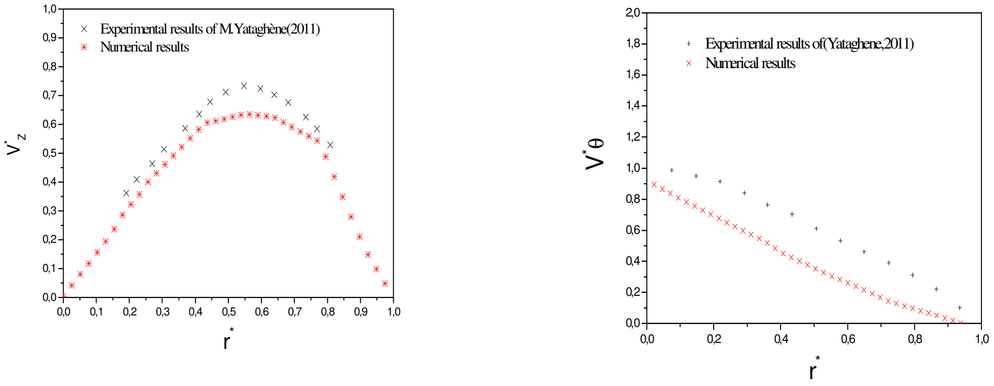


Figure 3. Comparison of the experimental and numerical
(left: axial velocity profiles, right: tangential velocity profiles)

For the axial component, a curved-type profile is observed, with a slight over-estimation, except in the region 0.5< r^*<0.6, this difference is explained by the experimental uncertainty which is around 10%[14] and the geometrical parameters (the fixation and the shape of blades).For the tangential component, the difference between the predicted and experimental values is bigger, especially when going closer to the rotor, because of the decrease in accuracy of PIV measurements in this region due to the poor transparency of the working fluid, which cannot be capture exactly by the capture camera digital. It seems that no accurate prediction can be achieved in this region, it must be noticed that this measurement is more difficult to experimentally conduct for the tangential component, especially for high rotation speeds. It can be noticed that the radial velocity results are not presented, where a zero values are observed for the angular position θ = 90° and the relative axial position Z*=0.2.

3.2 Influence of Taylor number

CFD simulation of scraped surface heat exchanger is carried out in this part, for both dimensions reported in Table I. An appropriate simulation model is selected using the Taylor number criteria. If Ta < 40, the flow is considered as laminar regime. For the case where Ta > 300, the k–ε model was enabled. Firstly, we define the following dimensionless magnitudes according to Mehel [12]. The dimensionless radius is:

$$X = \frac{r}{e} - \frac{R_t + R_r}{2e} \qquad (7)$$

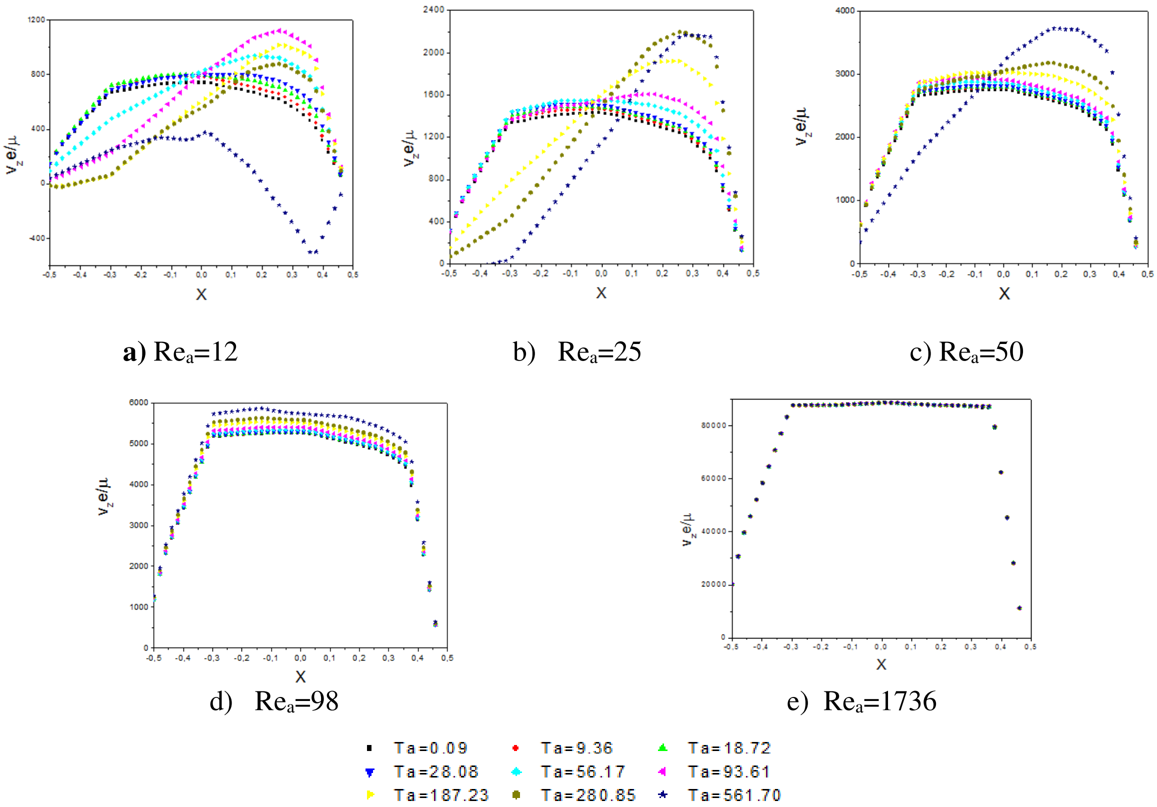
Where $e = R_t - R_r$ and z/e are dimensionless axial positions. The mean axial velocity component is normalized using the ratio e/μ, with μ, the cinematic viscosity. Usually, most authors on the SSHE compare this flow to that obtained by Couette-Poiseuille model where the axial velocity distribution is given by:

$$\frac{v}{v_0} = \frac{3n+1}{n+1}\left(1 - \left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right) \qquad (8)$$

Where: n represents the rheological behavior index for the power law fluid. Härröd [13] reported that any add of axial flow to the system contribute consequently to stabilize the rotational flow. To investigate the interaction between the swirling movements inducted by the rotation of blades rotor and axial flows, the radial distribution of the axial velocity is presented for different axial Reynolds numbers. The predicted dimensionless profiles are presented for a position located at Z=0.540 and for Taylor numbers ranging from 0.09 to 561.

Figure 4 show the evolution of the axial velocity profiles for Re_a =12, Re_a = 25, Re_a=50, Re_a =98 and Re_a =1736 respectively. For Re_a=12 (Figure 4a), the numerical investigation of the structure impact showed that for 0.09<Ta<28, the axial velocity profiles are parabolic. The same flow patterns were observed by Härröd [13]. Furthermore, for 56<Ta<280, the profiles are distorted in the presence of the blades with a maximum of the axial velocity near the interface between blades and stator. Indeed, the blades movement affects the hydrodynamic boundary layer developed on the stator wall. Next, in the region of (Ta=561, X=0.4), a flow inversion is observed, which means that the effect of rotational velocity is more notable than the axial flow rate. This assertion is corroborated in the work results produced by Yataghene [11] for higher rotational velocities.

In Figure 4b, for Taylor numbers 0.09< Ta <28.08, we noted that the axial velocity is proportional to the rotational velocity. It tends toward the classical laminar profile of a Taylor Couette flow. For higher Taylor numbers, namely, 56< Ta <93, the axial velocity changes its shape to initiate a negative slope in the zone 0.2<X<0.4. This zone can be considered as a transition zone wherein an onset of vortices takes place. For Ta numbers up to 187, the axial velocity profiles are completely modified while one maximum of the axial velocity is obtained close to the blades, at a distance equal to 3*X/4.We can explain this change by the apparition of the turbulent flow regime. If the axial velocity profiles are considered for Re_a=50 (Figure 4c), similar axial velocity profiles are obtained. However, the deformation has not been observed that for upper Taylor number values. Effectively, the transition zone appears at Ta=93 for Re_a=50, whereas this transition is already initiated at Ta=56 for Re_a=25. In addition, we must remark that the flow inversion was not observed as consequence of an increasing of the axial flow rate that plays an important role in effect reduction of the swirling flow induced by the rotation of the blades and stator. For any increasing of the axial velocity (Figure 4d and Figure 4e), the obtained axial velocity profiles are flat and the influence of the rotational velocity become negligible. We detected that by increasing of an axial flow-rate, it stabilizes the resulting flow heterogeneity in SSHE, particularly at the entrance and exit of the heat exchanger. This ascertainment is in perfect agreement with experimental observations of Wang [14], which have shown that, even for a Taylor vortices flow regime, the profiles of average velocities were remarkably similar to that the stable parabolic regime.



a) Re_a=12 b) Re_a=25 c) Re_a=50

d) Re_a=98 e) Re_a=1736

Figure 4. The axial velocity distribution versus radius and Taylor numbers for different axial Reynolds numbers

Next, to investigate the influence of the axial velocity on the flow patterns in the SSHE, the evolution of the axial velocity is presented versus the axial Reynolds numbers for a rotational velocity N = 0.5 rps at a position Z=0.540 m. To ease the figures reading, the predicted profiles are plotted for $12<Re_a<98$ in Figure 9a and for $1736<Re_a<2232$ in Figure 9b.

For all axial Reynolds numbers, a flat profile of axial velocity is observed with a light influence of the rotor and the blades rotation for lower values of Re_a. For higher values, example, Re_a=2232, the maximum axial velocity is about 1.22 times higher than the value predicted for Re_a=1736. This increase in the resulting axial velocity could be explained by the weak influence of the rotation of the rotor and blades. The same observations have been reported by Härröd [3], Naimi [4], Nouri et al. [15] and Yataghene et al. [7] in the case of a Newtonian fluid. If the results obtained by different operating conditions are compared. We distinguish three different types of flows, depending from the impact of the axial velocity. For little values of axial velocities, the flow in the SSHE is highly driven by the rotor and blades rotation. By increasing the axial velocity, an induced flow was noted as a result from complex interactions between the axial and swirling motions generated by the rotor and the blades rotation. Further, the increase of the axial velocity leads to a dominant axial flow.

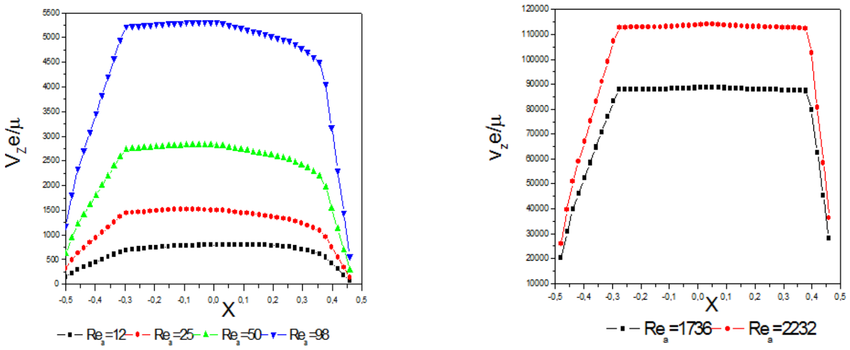


Figure 9. The axial velocity distribution versus radius and axial Reynolds numbers for N = 0.5 rps

3.3 Analysis of the shear rate distribution

It is well known that the presence of the blades along the SSHE tube causes a shear approximately similar to that caused by the rotation of the cylinder in the Taylor-Couette device [16]. Moreover, various direct observations of the flow (Newtonian and non-Newtonian) have shown that the shear had a tendency to be located between the blades and the tube wall. Consequently, it induces a field of heterogeneous gradients velocity in this region. Trommelen and Beek [1] , Naimi [4], Leuliet et al. [9], Dumont et al. [6] and Mabit et al. [17] . To corroborate this in our study case, we present, in Figure 10, the developed shear rate between the blade tip and the outer wall.

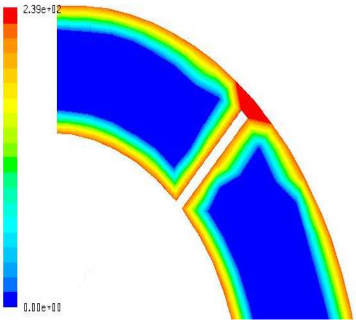


Figure 10. The distribution of shear rate between the blade tip and outer wall

The shear rate distribution shows that the velocity gradients in the zone close to the tip of the blade for Newtonian fluids are significantly higher than that occur in the rest of the volume. However, more important shear rates occur between the edge of the blade and the outer wall surface.

4. CONCLUSION

This numerical study is performed using the commercial CFD code FLUENT to predict the distribution of the velocity fields and the shear rate in a SSHE designed for deparafining of oil. A comparison of our results with Yataghéne's experimental works is carried out while showing a satisfactory agreement between both velocity profiles. Then, a thorough investigation of phenomena in the SSHE shows that the resulting flow is depended of the mass flow rate. Furthermore, in relation with the axial flow, three different cases of flow regimes are observed. For weak values of axial velocities, the flow in the SSHE is highly driven by the rotation of rotor and blades. By increasing of the axial velocity, a resulting flow is found as a result from a complex interaction between the axial and the swirling motions due to the rotation of rotor and blades. We have noted that an increasing of the axial velocity leads to a dominant axial flow

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