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- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100th Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Parametric study of two-phase flow in cyclonic separators for gas industry with application to gas turbines

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Abstract

In this work numerical analysis is used to carry out a parametric study of two-phase flow water-gasoil in a compact cyclonic separator (CCS). The study is oriented to produce a set of range parameters that may be used as a guide to control and manage multiphase mixtures separation with application to the gas industry, especially gas turbines. The cylindrical geometry under study has an aspect ratio of $R = 2.5$ (where R = height/diameter). The CCS has two exits: one on the top for light liquid flow and one tangentially located in the bottom for heavy liquid flow. A finite volume approach has been employed with body-fitted coordinates in a 3-D solution of the liquid-liquid cyclonic flow. The turbulence was resolved using a RNG model, while the interactions between each component of the flow were addressed using a slip mixture model. The mixture under study is immiscible, and limited to the composition between 0.3 and 0.7 for water and consequently, from 0.7 to 0.3 for gasoil. The results indicate that the separation is sensitive to exit pressures, viscosity of light component gasoil and bubble size of the gasoil.

Keywords: Cyclonic separator; Turbulence modeling; Two-phase flow; Particle trajectory

Nomenclature

$\bar{a}$ – bubble acceleration,
u – fluid velocity,

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u_m – mixture velocity,
u_p – bubble velocity,
p – pressure,
F_i – body forces,
g_i – gravity force,
d_p – secondary phase bubble diameter,
u_{Dk} – k-phase directional velocity,
u_k – k-phase velocity,
u_m – average mixture velocity,
ρ_k – k-phase density,
ρ_m – mixture density,
ρ_p – secondary phase density,
u_q – primary phase velocity,
u_p – secondary phase velocity,
v_{qp} – slip or relative velocity,
α_k – k-phase volumetric fraction,
n – number of phases,
μ – molecular viscosity,
μ_m – viscosity of mixture,
μ_q – primary phase viscosity,
τ_{qp} – relaxation time,
k – phase number,
i – i-direction,
j – j-direction,
q – primary phase,
p – secondary phase.

1 Introduction

The fuel burning process during powering gas turbines requires ensuring that the fuel is managed as clean as possible. This practice may prevent a variety of effects and problems like deposits, erosion or corrosion of internal parts, which in the less causes a drop-down of the efficiency or alters the scheduled overhauls [1]. Impurities contained in the mixture of combustion has large impact also in the power output. In this respect, the gas industry requires low cost, low maintenance, easy of operation and high efficiency separators to clean as much as possible the mixtures naturally coming out from under ground natural deposits. During the last decade, the compact cyclonic separators (CCS) have attracted the attention because a number of advantages over the large, time consuming, gravitational precipitators. Mixtures of up to three components may be separated in a CCS as recent numerical computations have proved [2]. A compact separator consists of a cylindrical vessel doted of tangentially located inlet and outlet, and an extra upper outlet for the slighter phase. It uses the principle of cyclone to create interaction of the phases contained in the mixtures that require cleanness and separation. Two main flow streams develop at the interior of the CCS: one downwards, peripheral that keeps high rotation rates, and one ascending through the central region close to the vertical axis of the cylinder [3]. The CCS has however a number of drawbacks. One of the most important is the poor understanding of the complex cyclonic flows and how it promotes or prevents the mechanism of separation itself. Also, a lack of information about the range of operation in terms of pressure, component properties, velocity inlet and aspect ratios shadow their massive utilization [4]. In this work a parametric study of a two-phase flow in a CCS is presented. The study is oriented to produce a set of range parameters that may be used as a guide to control and manage separation of this kind of mixtures with application to the power industry. The cylindrical geometry under study has an aspect ratio of $R = 2.5$ (where $R =$ height/diameter). It has two exits: one on the top for light liquid and one tangentially located in the bottom for heavy liquid. A finite volume approach has been employed with body-fitted coordinates in a 3-D solution of the liquid-liquid flow. The turbulence was resolved using a Renormalized Theory Model (RNG), while the interactions between each component of the flow were considered and addressed using a slip mixture model. The mixture considered was water-gasoil, where this last one has a density of 830 kg/m^3 and a chemical formula: $C_{16}H_{29}$. It has been assumed that both components of the mixture are immiscible. The composition of the mixture was investigated within the range from 0.3 to 0.7 for the volumetric fraction of water and, consequently from 0.7 to 0.3 for the gasoil phase. The results indicate that the separation process is sensitive to operation parameters like exit pressures, viscosity of gasoil and bubble size of slight component. A pressure *vs* mass flow plot shows the behavior of the composition in both outlets for a range of operation conditions. This result can help for avoiding undesired over-concentration of one component, which may affect the manage of residuals after separation. The bubble size of the slight component was observed to affect the separation process such that the largest the bubble of gasoil, the better the separation. This parameter is related with the velocity conditions of the mixture flow at the inlet, but it also defines the residence time of the flow during the operation of the CCS, which affects the separation too. Furthermore, the separation efficiency is discussed as a function of the viscosity of the light liquid phase.

2 Methodology

The fluid dynamics of the separation process of two-phase flow water-gasoil is resolved numerically through the Renormalization Group Theory RNG model for turbulence [5]. A finite volume approach has been employed with body-fitted coordinates in a 3-D solution of the liquid-liquid cyclonic flow. In turn, to take into account the interaction between each phase flow, a slip mixture model is used further. This model was formulated for both fluid-fluid and fluid-bubble. A relative velocity is considered for each phase flow, which makes it possible to resolve the movement of each phase flow moving at different velocity from each other. The mass and momentum conservation equations for incompressible flows plus a volumetric fraction equation for the secondary phase are considered and solved using algebraic expressions for the relative velocity, in a segregated scheme. No chemical reactions are taken into account. The slip mixture model has been successful in modeling different problems of fluid flow like sedimentation, cyclonic separation and bubble-continuous phase flow [6, 7]. The mass conservation equation for the mixture under consideration reads:

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x_j}(\rho_m u_{m,j}) = 0 \tag{1}$$

where ρ_m is the mixture density, expressed as:

$$\rho_m = \sum_{\kappa=1}^{n} \alpha_\kappa \rho_\kappa \tag{2}$$

where k is the phase number and summation of individual contributions form each phase flow applies in the momentum conservation equation:

$$\begin{aligned}\frac{\partial}{\partial t}\rho u_{m,i} + \frac{\partial}{\partial x_j}\rho_m u_{m,i} u_{m,j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\mu_m\left(\frac{\partial u_{m,i}}{\partial x_j} + \frac{\partial u_{m,j}}{\partial x_i}\right)\\ +\rho_m g_i + F_i + \frac{\partial}{\partial x_j}\sum_{\kappa=1}^{n}\alpha_\kappa \rho_\kappa u_{D\kappa,i} u_{D\kappa,j}\end{aligned} \tag{3}$$

μ_m is the molecular viscosity for the mixture:

$$\mu_m = \sum_{\kappa=1}^{n} \alpha_\kappa \mu_\kappa \tag{4}$$

$\overline{u}_m$ is an average velocity

$$\overline{u}_m = \frac{\sum_{\kappa=1}^{n} \alpha_\kappa \rho_\kappa \overline{u}_\kappa}{\rho_m}. \tag{5}$$

Using the slip model we assume a local equilibrium of all phase flow at small space scales. A relaxation time $\overline{\tau}_{qp}$ that takes into account the presence of any other phase, is introduced as:

$$\overline{\tau}_{qp} = \frac{\rho_p d_p^2}{18\mu_q} \tag{6}$$

to define the time it takes for a bubble with density ρ_p and diameter d_p to accelerate within the continuous phase, giving place to the slip velocity as:

$$\overline{v}_{qp} = \overline{\tau}_{qp}\overline{a}$$

Details of the mixture model are given elsewhere [6, 8].

3 Separator geometry and boundary conditions of computational model

A cylindrical geometry in 3-D of aspect ratio $R = 2.5$ was considered for solving the flow dynamics of the mixture in the CCS using the program Fluent V6.2 [9]. The CCS has an upper mixture tangential inlet of 0.1×0.01 m cross section, placed at 0.36 m from the basis. It has also a tangential outlet for heavy liquids placed in alignment with the tangential inlet, but at 0.05 mm from the basis. The finite volume approach was used with the SIMPLE algorithm to couple the pressure to the velocity equations. A body fitted coordinate model of the cyclonic separator was constructed and non-structured meshed to have 67000 elements. Figure 1 shows an isometric of the CCS under study with some physical aspects of the main currents observed in this configuration. A set of stations for reporting the results obtained are indicated in this figure. These stations will be used to report velocity profiles in terms of the total height, $h = 0.47$ m, as: $s_1 = 0.87$, $s_2 = 0.76$, $s_3 = 0.66$, $s_4 = 0.26$ and $s_5 = 0.06$. The boundary conditions applied to the cylindrical cyclone are presented in Tab. 1.

A first exercise was carried out in order to validate our results by comparing directly with those reported in the literature by Farchi [10]. The corresponding conditions appear in the first column after the boundary conditions type. Afterwards a set of boundary conditions were applied with geometrical and fluid mixture changes. The third column refers to a CCS with an upper exit reduced in diameter by 1/3. The composition used is indicated in volume fraction. In this configuration the two outlets were used for conducting a parametric study by imposing a set of fixed pressures each at a time covering a range from 0 to 3000 Pa while keeping constant to $P = 0$ the other one. The parametric study was extended to investigate CCS performance under viscosity variations of slight component from 3.32×10^{-5} to 3.33 kg m^{-1} s^{-1}. The range of gasoil bubble under study was from 50 to 5000 μm.

4 Results and discussion

4.1 Two-phase flow: water-air

The results of Farchi [10] are shown in Fig. 2 together with our results for the flow conditions specified in column 2 of Tab. 1. A good agreement can be observed in the amplitude of tangential velocity registered at station one of the CCS, which corresponds to a height just on the lower part of the tangential inlet (see Fig. 1). An under-prediction of 14% compared with the experimental data

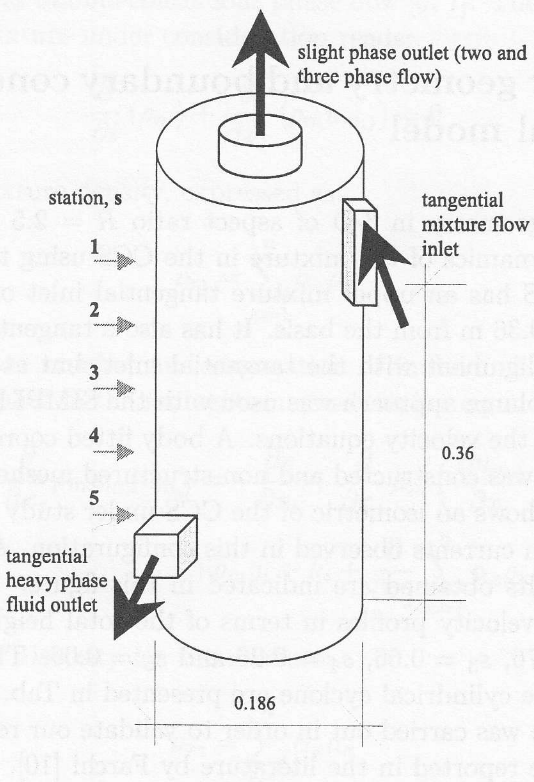

Figure 1. Scheme of the flows in a compact cyclonic separator. Dimensions are in m.

is observed in a region that goes from near the wall to the central axis. This is due to a small difference of mass flow of inlet, 2.99 instead of 2.66 kg/s in Farchi, [10]. A larger mass flow develops larger magnitudes of tangential velocity and this on time has an effect on the speed of the raising central vortex current to balance the velocity vector. This is why the tangential velocity profile has smaller magnitudes in the center region of the separator at station, s_1. The tangential velocity increases as the wall is reached in the peripheral zone.

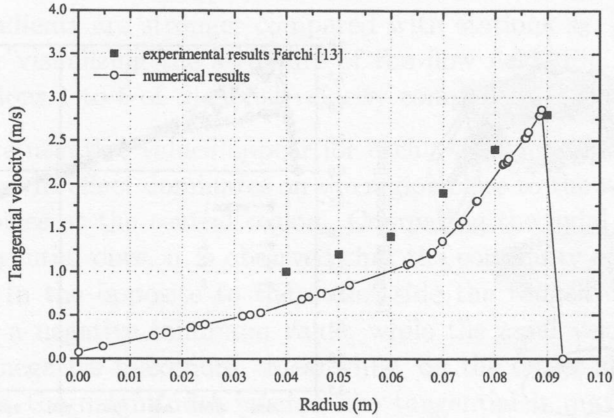

Figure 2. Direct comparison of numerical with experimental results for a two-phase flow in a CCS.

Table 1. Boundary conditions applied in the numerical simulation of CCS.

Boundary condition type	Two-phase flow water-air (0.71 to 0.29) Comparison with [13]	Two-phase flow water-Gas oil (0.3 to 0.7)
Inlet (mass flow, velocity)	2.66 kg/s	3.382 kg/s, 4.2 m/s
Top outlet (pressure)	$P = 0$ top exit without reduction	$P = 0$ top exit **with** reduction
Tangential outlet (pressure)	$P = 0$	$P = 0$ and 0 to 3000 Pa
Wall	$\vec{u} = 0$	$\vec{u} = 0$

4.2 Two-phase flow: gasoil-water

The velocity vectors corresponding to the conditions of column 3 in Tab. 1 are shown in Fig. 3a. It is observed that the vortex activity decreases as the flow goes down due to the tangential exit placed at the bottom, that slow down the tangential velocity by forcing the fluid exiting the CCS. A plot of the profiles of velocity components, tangential and axial, against the ratio may help to understand the complexity of the flow. Figures 3b and 3c show a set of profiles of velocity distribution from wall to wall. As observed, the tangential velocity reaches magnitudes of different order on the extremes, being smaller on the side of the tangential outlet. The effect decreases as we approach the bottom region, stations s_4 and s_5. Over there the magnitude is the same and balances the profile. Looking at the entrance region, the profiles of stations 1 and 2 show that

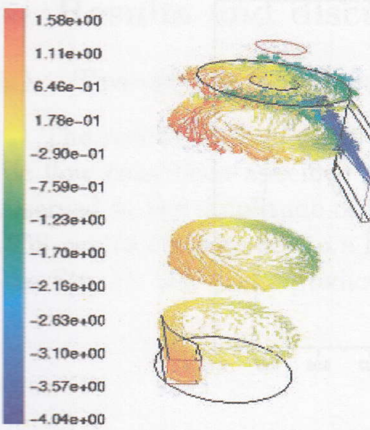

Figure 3a. Tangential velocity vectors for two phase flow in the CCS, water-gasoil.

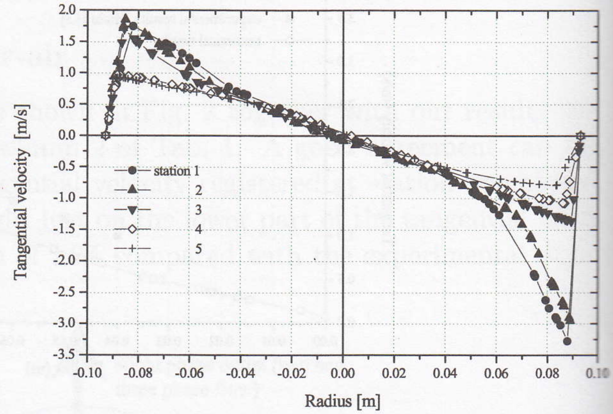

Figure 3b. Tangential velocity profiles for two phase flow in the CCS, water-gasoil.

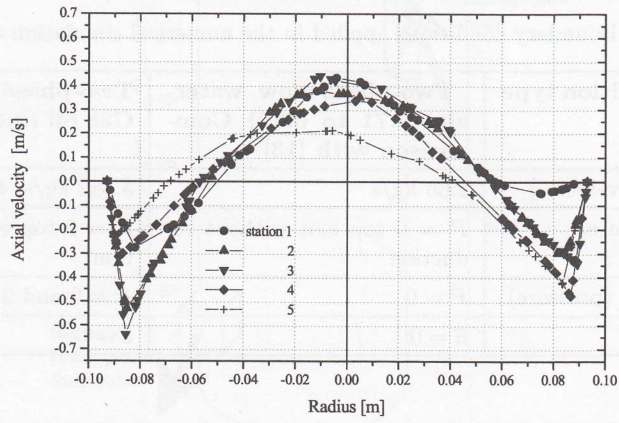

Figure 3c. Axial velocity profiles for two phase flow in the CCS, water-gasoil.

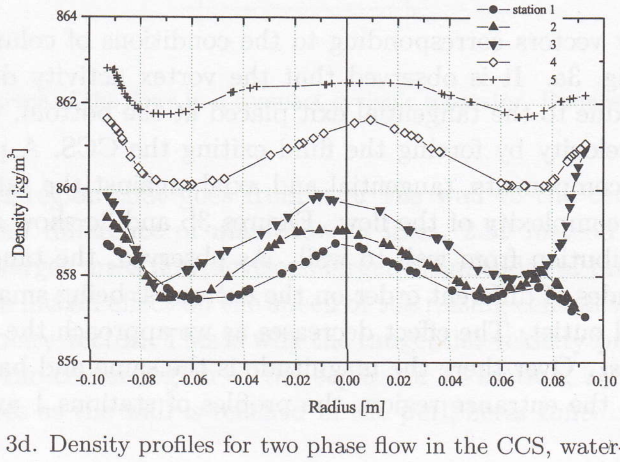

Figure 3d. Density profiles for two phase flow in the CCS, water-gasoil.

the velocity gradients are stronger compared with stations s_3, s_4 and s_5. As a complement for visualizing the structure of the flow field, Fig. 3c presents the profiles for stations 1 to 5 of the axial velocity component.

In this figure negative values appear for each velocity profile indicating that the downwards swirl effect dominates on the region close to the wall. Instead, the up flow takes place at the central region. Comparing the axial velocity profiles against the tangential ones, it is observed that the continuity equation balances the flow rate. In the opposite to the outlet side the tangential velocity component reaches a negative minimum value, while the axial velocity component approaches its negative maximum. Meanwhile, on the outlet side wall extreme on the contrary, the magnitudes inverse, the tangential is maximum while the axial is minimum. Focusing on the up flow region, a maximum takes place at the upper zone of the CCS, say, the flow accelerates upwards close to the upper outlet. The tangential component indicates, however, that there is no swirl effect at all in the central region with zero magnitude of velocity, as reported also by other investigators [4, 5].

A less attended picture of the flows in a CCS is the one referred to the density. In Fig. 3d we present a set of profiles of density taken also at stations 1 to 5. These profiles indicate that a region of denser fluid is found in the lower parts of the CCS flow, showing clearly the effect of separation: the upper part is occupied by slighter fluid. The profiles of stations 1 and 2 indicate that lighter fluid has been separated from the mixture and directed to the upper outlet. Symmetry is observed in the density profiles except in the one for s_5. Such a lack of symmetry is also observed in the axial velocity profile for the same station.

4.3 Parametric study of two-phase flow: water –gasoil

In this section we present a study that shows how the flows and the performance of a CCS can be affected by operation conditions that may vary according to industry applications. The study is directed to emphasize the importance of ensuring control of these operation conditions. The results can be useful for applications where even a good control of the parameters studied, the performance of the CCS is observed to be a function of natural properties of an under ground mixture like the viscosity. Other parameters can be manipulated like the inlet velocity, though their range of operation is rather a function of cost. A quantification of their effect on the CCS performance can help to estimate the impact of an order of magnitude more or less of exit pressure or bubble size for instance.

4.3.1 Pressure at the exits

The change of pressure at the exit produces a strong effect on the operation of CCS since the velocity field is modified according to any increment or decrement of discharge pressure. The study concentrated in a range of pressure that can be present in field installations. Figure 4 contains a plot where the mass flow of each phase in the bottom exit is plotted as a function of the discharge pressures. The pressure was varied in one exit at a time while keeping constant the other one. Variations of exit pressure up to 3×10^3 Pa were investigated. As can be seen in this figure, three levels of the constant pressure were investigated: 0 Pa, 500 Pa and 1500 Pa. The effect of such pressures on the CCS performance is notorious, especially because these conditions impact directly on the mass flow rate of each phase flow obtained at the exits. It is observed that a maximum pressure of 2×10^3 Pa is allowed for the bottom exit keeping constant the upper exit, since the mass flow rate of both the water and gasoil is drop down to an inadmissible magnitude close to zero. On the contrary, the advantage of applying for instance 1000 Pa to the upper exit while keeping the bottom exit fixed to 500 Pa is a 16% more water inventory in the bottom exit, compared with the normal conditions of operation (zero pressure at both exits). This result indicates a separation improvement since more water through the bottom exit means less water through the upper exit. The upper stream becomes thus enriched in gasoil by 1 %, which may increase to 3% if we operate the bottom exit at 2×10^3 Pa instead of 1×10^3 Pa.

What is observed in the next figure for the results at the upper exit confirms these observations. For the same conditions (1000 Pa applied to the upper exit while P_{bottom} is fixed to 500 Pa) we observe that 34% less water is exiting through the upper exit, which is very good in terms of performance, while the contents of gasoil through the upper exit is no more than 13%, compared with the normal operation conditions.

4.3.2 Viscosity of gasoil

A study of the separation process when it is affected by viscosity magnitude is showing that the mixture can be separated more efficiently at normal ambient conditions, say normal ambient temperatures. The mixture can experiment variations of viscosity attending to low or high temperatures of operation. One plot of mass flow rate of each component against the gasoil viscosity allows one to observe that a large effect of gasoil viscosity increments can be expected. Figure 6 shows the plot where a strong dependence of the water mass flow rate as a function of the slighter phase component viscosity is observed. This information can be improved with the behavior of gasoil viscosity as a function of temper-

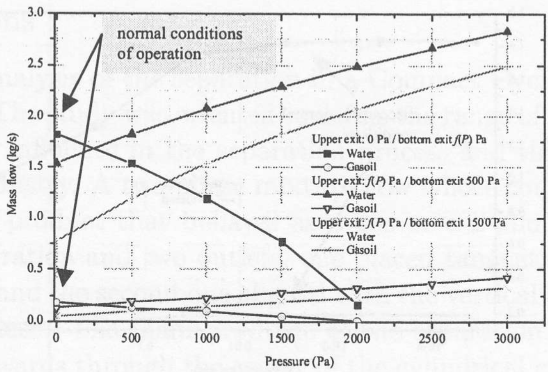

Figure 4. Mass flow of two phases through the bottom tangential exit as a function of the pressure in both exits for the composition water: 0.7, gasoil: 0.3.

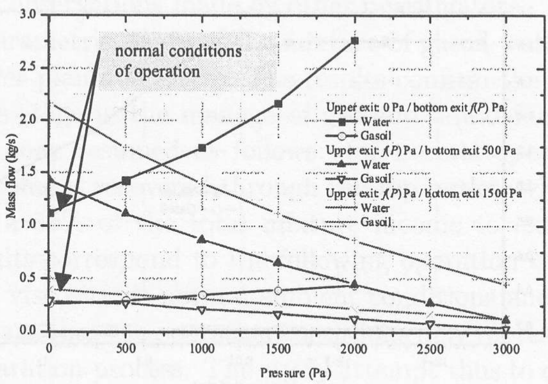

Figure 5. Mass flow of two phases through the upper exit as a function of the pressure in both exits for the composition: water: 0.7, gasoil: 0.3.

ature for which the reader is referred to the specialized literature. The plot in Fig. 6 shows that the mass flow rate of water exiting through the bottom exit is affected by a 23% if the gasoil viscosity grows two orders of magnitude, which may be expected in cases when the CCS is operated at low temperatures, for instance. The mass balance counteracts this result for the upper exit, where the same change of gasoil viscosity produces an increment of water mass flow rate, which is observed in a plot not shown in this paper.

The viscosity has been envisaged as an agent affecting processes like mixing-up in biotechnology systems [11]. The evidence here is that any increment of viscosity does not favors the separation.

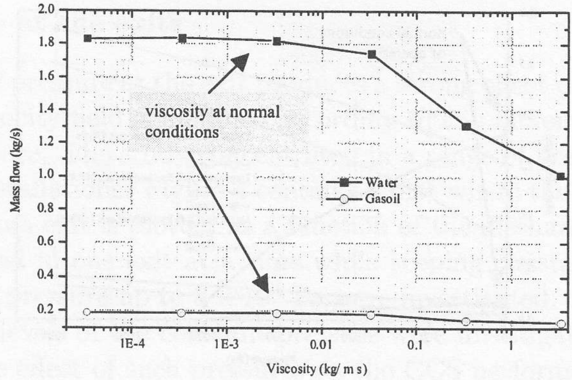

Figure 6. Mass flow of two phases through the bottom exit as a function of the gasoil viscosity for the composition: water: 0.7, gasoil: 0.3.

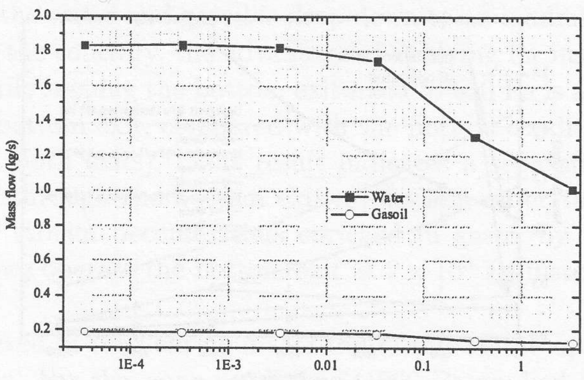

Figure 7. Mass flow of two phases through the bottom exit as a function of the gasoil bubble size for the composition: water: 0.7, gasoil: 0.3.

4.3.3 Bubble size of slight phase component

The study of the size of secondary phase (gasoil) was conducted attending to the bubble size. This study revealed that the larger the bubble of gasoil, the better the separation in terms of the mass flow rate of the heavier phase obtained through the bottom stream. Figure 6 shows the trend of mass flow rate as a function of the bubble size in microns. It is clear that larger drops or bubble of lighter phase component increase the separation in a 17.2% (1000 microns compared with 50 microns). It is not clear however, how to control this parameter, but what is known is that two phase flow patterns, which are definitively linked to the size in question, are function of operation conditions [12].

4.4 Conclusions

A numerical analysis of the separation in a Compact Cyclonic Separator has been carried out. The study was oriented to define the range of a set of parameters that may have an influence in the separation process and their applicability to the gas turbine industry. A two-phase mixture flow whose components are water and gasoil (an oil product that behaves as a gas or a liquid). The CCS has a cylindrical configuration and two outlets, one placed tangentially in the bottom for heavier phase, and the second one aligned with the vertical axis of the cylinder for the slighter phase. The main products of the separation in a CCS are one stream moving upwards through the center of the cylindrical cross section, which is almost free of heavier phase; and one stream moving in rotational form close to the wall, which contain mostly of the inventory of the heavier phase present in the total mixture income. The results for specific conditions were compared with experimental observations made by other investigators. The agreement was good allowing a parametric study of the mixture of gasoil-water with application to the oil and power plants industry. The results confirm the advantage of using a CCS as previous stage in the manage of gas and liquid fuels. The results for this configuration may resumed as follows: for normal operation conditions a 41.8% of gasoil income is recovered through the top outlet, while a drag of water occurs producing a 59% of the total mixture income to exit through the top outlet. These results correspond to the following operation conditions: pressure at outlets = 0 Pa, viscosity at normal ambient conditions and gasoil bubble size = 50 μm. This means that the operation conditions may represent a key factor for improving the separation process. The study attempt thus to define the influence of exit pressure, viscosity of slighter phase component and its bubble size, on the separation process. The results revealed that operating the CCS at pressures of 2×10^3 Pa and 0.5×10^3 Pa the top and bottom exits, respectively, we obtain a gasoil richer stream through the top exit by 3%. An increment of gasoil bubble size from 50 to 500 μm improves the inventory of gasoil though the top outlet by 17%, and with a further increment to 1000 μm the percentage goes to 81%, respectively. In terms of viscosity the inventory of water through upper stream can be increased by up to 23% just because increasing the gasoil viscosity by two orders of magnitude. This result is especially interesting for off-shore platforms in the North Sea where very low temperatures prevail. Finally, the bubble size of 1000 microns of the slighter phase component can improve the separation process by up to 17%, provided the normal size is 50 microns.

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