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Oil & Gas Science and Technology – *Rev. IFP*, Vol. 57 (2002), No. 1, pp. 99-107

Multiphase Pumping:

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Résumé — **Pompage polyphasique : réalisations et perpectives** — Le pompage polyphasique est maintenant largement accepté par l'industrie pétrolière. Le présent article décrit les performances actuelles de la technique de pompage hélico-axiale inventée et développée par l'*Institut français du pétrole (IFP)*. La taille des pompes installées a considérablement augmenté à mesure que l'accumulation de l'expérience obtenue sur les champs, à terre ou offshore, donnait confiance aux exploitants. Une seule pompe peut désormais développer une puissance de 6 MW et les pompes hélico-axiales sont actuellement les plus grosses pompes polyphasiques construites dans le monde.

Des travaux de recherche sont toujours effectués par l'*IFP* pour améliorer les performances des pompes hélico-axiales ainsi que pour développer de nouvelles applications des turbo-machines hélico-axiales : ré-injection des gaz acides en solution, compresseurs de gaz humides, turbines polyphasiques. L'article décrit les principaux axes de travail et les méthodologies utilisées pour ces développements. Les techniques expérimentales et numériques les plus avancées sont utilisées à cet effet : anémométrie Doppler laser du coté expérimental, simulations d'écoulements diphasiques et optimisation des formes par réseau de neurones et algorithme génétique du côté conception et calcul des cellules hydrauliques.

Mots-clés : production polyphasique, pompage polyphasique, pompe hélico-axiale, réinjection des gaz acides, turbine polyphasique, compresseur de gaz humide, visualisation d'écoulement, anémométrie Doppler laser, simulation en mécanique des fluides, simulation d'écoulements diphasiques, optimisation des formes.

Abstract* — *Multiphase Pumping: Achievements and Perspectives — *Multiphase pumping receive now a widespread acceptance of the oil industry. The paper describes the state of the art performance of the helico-axial technology invented and developed by the* Institut français du pétrole (IFP). *The size of the installed pumps has considerably increased as the industry gained confidence with the accumulation of field experience, both onshore and offshore. A single pump can rate up to 6 MW to-date, and helico-axial pumps are the largest multiphase pumps manufactured in the world.*

Further research works are still performed at IFP *to improve the helico-axial pump performance but also to develop new applications of multiphase turbomachines: sour gas re-injection in solution, wet gas compressors, two-phase turbines. The paper describes the main axes of works and the methodologies applied for these developments. The most advanced experimental and computational techniques are used: laser Doppler anemometry on the experimental side, two-phase CFD simulation and shape optimisation by neural network and genetic algorithm on the design and calculation side.*

Keywords: multiphase production, multiphase pumping, helico-axial pumps, sour gas reinjection, two-phase turbine, wet gas compressor, flow visualisation, laser Doppler anemometry, CFD simulation, two-phase flow simulation, shape optimisation.

INTRODUCTION

Multiphase pumping is a long-established activity in the Department of Applied Mechanics of the *Institut français du pétrole (IFP)*. First works were initiated in the seventies to extend the application of downhole electrical submersible pumps. Figure 1 shows the first 3-stage pump prototype tested on a multiphase loop.

In the mid-eighties, multiphase pumping raised a renewed interest to transport the production of subsea satellite fields. At that time, subsea satellite developments were frequently substituted to stand-alone platforms in the North Sea to reduce offshore development costs. As tied-back distances to existing facilities were limited between 15 and 20 km due to the available natural reservoir pressure, multiphase pumps appeared as a possible means of increasing these distances by adding energy to the liquid-gas mixture (Falcimaigne, 1992).

A multiphase pump development was initiated in 1987 in the Poseidon Project, joining *Total*[1], *Statoil* and *IFP* (Arnaudeau, 1988; Engelman and Torp, 1990). This project, funded by the European Union, resulted in a prototype pump, the P300, designed for a total volumetric flow rate of 250 m^3/h (gas plus liquid), with an actual gas fraction of 91% at suction. The pump was driven by a 500 kW electrical motor.

After an extensive test programme on an *IFP* multiphase loop to investigate the hydraulic and mechanical behaviour in steady-state and slug flows, the P300 pump prototype was tested in 1991 and 1992 at Sidi El Ytayem, a Tunisian field operated by *Total* (Gié, 1991). This prototype is still in service in an *IFP* experimental loop, ten years later, to boost multiphase mixtures.

(1) Now *TotalFinaElf.*

Figure 1

The first helico-axial pump prototype under tests.

First field applications of the Poseidon technology were characterised by relatively low flow rates and powers. Typical examples are the pump installed in the *TotalFinaElf* Pecorade field, in south of France, with a capacity of 360 m^3/h and drive power of 600 kW (Falcimaigne *et al.*) 1994; Leporcher and Taiani, 1995), or the pump installed in the *Statoil* Gullfaks A Platform in the North Sea with a total capacity 200 m^3/h and drive power of 750 kW (Vangen *et al.* 1995). A subsea helico-axial turbo-pump was also installed in 1994 at the Draugen field in the North Sea by Norske Shell.

The progressive accumulation of field experience secured the oil operators to apply the technology on a larger scale. The power of recent Poseidon pumps reaches 4.5 MW for the *TotalFinaElf* Dunbar field in the North Sea and 6 MW for the Yukos Priobskoye oilfield in Siberia (total flowrate capacity: 3300 m^3/h). Helico-axial pumps are the largest multiphase pumps in the world to date, both in capacity and power, and also the deepest in the world for subsea applications (550 m water depth in Topacio field, Gulf of Guinea). These two outstanding cases are briefly described in the paper after a description of the performance range of helico-axial pumps.

The technical and commercial successes of multiphase pumps open new perspectives for the technology. The development of new design methods may lead to significant improvements of performance and efficiency. New types of applications may be considered as well. The paper aims at presenting the research underway at *IFP* in these two directions.

1 HYDRAULIC DESIGN OF HELICO-AXIAL PUMPS

Multiphase helico-axial pumps are multistaged pumps. Each stage is composed of a rotating part, the impeller, and a static part, the rectifier. The number of stages depends on the required head. Up-to-now, the highest number of stages is 15 and is only limited by the dynamic behaviour of the rotating assembly.

A typical helico-axial compression cell is shown in Figure 2. The special shape of the impeller (rotating part) limits accelerations and also low-pressure zones. The initial shape was invented in the late seventies by our pioneering colleagues Souriau and Arnaudeau. This shape was improved later several times. It avoids the phase separation and facilitates the gas carry over, providing so good performance in multiphase flow. In ordinary compression cells, the liquid is accelerated and flowed while the gas remains in place, leading quickly to the gas-locking phenomenon.

Figure 2

Helico-axial multiphase compression cell.

Up-to-now, commercial helico-axial multiphase pumps have been manufactured with impeller diameters from 188 mm to more than 400 mm (and also with smaller diameters on test machines: 75 and 135 mm). Rotation speeds are usually chosen between 3500 rpm et 6500 rpm. This makes possible total volumetric flowrates ranging to-date from 150 to 3300 m^3/h (total flowrate is gas flowrate plus liquid flowrate).

Multiphase pumps in service have been designed for gas volumetric fractions (GVF) between 50% to 93% (*i.e.* gas to liquid ratios of 1 to 15). However, actual gas fractions can vary from 0 to 100% and pumps have already been run on fields with 100% gas during several days without problems.

The gas volumetric flowrate is reduced during the compression of the multiphase mixture, as in compressors, and the design of the stages is adjusted every three, four or five stages to provide the best performance. Helico-axial multiphase pumps are in fact hybrid turbomachines which combine features of both rotodynamic pumps and multistage axial compressors. For instance, as in compressors, the inlet pressure influences the mixture compressibility and has an impact on the compression performance.

As any turbomachines, multiphase pumps deliver basically a head. Differential pressures between suction and discharge depend on multiphase mixture densities. This is not a drawback as advanced sometimes by contenders or competitors, but rather an advantage because most of the cases requiring a pump are driven by head and not pressure (*e.g.* difference of elevation or friction losses in pipes). So, within some limits, the pump can adjust itself to variations of pressure resulting from gas fraction variations.

Eventhough a multiphase pump is designed for a given duty point for best performance, it can cover a wide operating domain of gas fractions, suction pressures, flowrates, especially if it is driven with a variable speed motor. This is an advantage since the production evolves with time and forecasts are not always accurate.

Multiphase transportation over long distance has been made possible by simulating both steady and transient flows in a pipeline coupled with a multiphase pump (Heintzé *et al*., 1999).

2 EXAMPLES OF FIELD APPLICATIONS

First applications of multiphase pumping were relatively small scale projects to boost few low pressure wells to an existing high pressure separator, avoiding to flare the low pressure gas. Recent applications are larger scale projects with high capacity and high power pumps. In these applications, cost saving may reach 30% by using multiphase pumps instead of conventional development schemes.

Significant commercial successes have been achieved and helico-axial multiphase pumps have been installed onshore or offshore in a variety of environments and climates, such as: Siberia (Korolov *et al*., 1999), Middle East, South East Asia, Africa and in the North Sea.

As mentionned in the introduction, helico-axial pumps are to date the largest installed multiphase pumps in capacity and power (Dunbar field in the North Sea and Priobskoye field in Western Siberia), and the deepest for subsea applications (Topacio field). The Dunbar case, largest in power offshore, was recently presented in detail, including the field experience after two years of operation (Leporcher *et al.*, 2001). The two other recent applications are briefly described hereunder.

2.1 Priobskoye Case

The multiphase pumps are installed in the part of the Priobskoye field extended on the right bank of the river Ob, in Western Siberia. This part of the field is operated by the Yukos' operating company *JSC Yujanskneftegas*. The climate is rough (temperatures range from –55C to +35C). The area is swampy and difficult to access, being in the flood plain of the river Ob, and environmentally-sensitive. For these reasons and also because of a significant cost saving, the multiphase pump option was selected by the operator (Pershukov *et al*., 2001).

The pumps were designed and manufactured by *Sulzer Pumps*. Two pumps have been commissionned and started in summer 2001. Two other ones are currently under fabrication. The two multiphase pumps are used to export a production of 90 000 barrels of oil per day (bopd) in a single 30 km long pipeline to a processing facility located on the oldest part of the field, on the left bank of the river. Each pump is designed for a total suction flowrate of 3300 m^3/h and they are driven by a 6MW variable speed electrical motor. When the four pumps and a second pipeline are in service, the total production will reach 200 000 bopd.

2.2 Topacio Case

The Topacio field is located in Equatorial Guinea, in deep water (500 m water depth). Its operator is *Exxon-Mobil.* It is developped as a subsea satellite of the Zafiro field, 8.5 km far away. The Zafiro field is produced by a FPSO[2], the Zafiro Producer. Two Poseidon helico-axial pumps are installed on a subsea module (Skiftesvik and Særen, 2000). They boost four subsea wells. The gas fraction at suction (GVF) is around 75% to 80%. Each pump has a nominal capacity of 470 m3/h. Suction and discharge pressures are respectively 2.5 and 6.0 MPa. The pumps are driven by an electrical motor of nominal power 870 kW. The electrical power is generated at a variable frequency on the FPSO and supplied at 11 000 V to the pumping station by an electrical cable. A subsea electrical step-down tranformer is located near the pumping template to feed the electrical motor at a lower voltage.

The subsea pumping station was designed and manufactured by *Framo Engineering* in Norway. The station was started in summer 2000 and was run until now without problem.

3 NEW POTENTIAL APPLICATIONS

3.1 Combined Reinjection of Sour Gas and Water

The processing of hydrocarbons very often produce acid gases (carbon dioxide CO_2 and hydrogen sulphide H_2S) which are either rejected into the atmosphere when they are produced in very small quantity, treated (with production of sulphur in the case of H_2S) when they are produced in very large quantity or reinjected in depleted reservoirs, aquifers (Sleipner) or oil reservoirs. In addition, the oil production is very often accompanied by the production of salt water at ground level which needs to be either treated or reinjected into the ground.

At least three pilots of reinjection of acid gas in dissolution in water have been tested for several years in Canada, the mixture being reinjected either in depleted reservoirs or aquifers. The present units of reinjection include, upstream of the wellhead, single phase compressors for the sour gas and pumps for the liquid, the two fluids being mixed downstream in order to obtain the total dissolution of the gas into the water and the reinjection of a single phase fluid (Longworth *et al*., 1996).

It appeared, some years ago, that units currently used could be simplified considerably by first mixing the effluents at the produced pressure then rising the pressure by using a helico-axial multiphase pump. This second solution presents several advantages: reduction in weight and footprint (particularly attractive for offshore operation), in induced vibrations (removal of reciprocating compressors) and in capital and operating costs. On the other hand, this second solution might present, in certain situations, a lower efficiency, particularly when the inlet pressure is very low (after a gas treatment with amines: 0.15 to 0.20 MPa abs).

A research program was launched in 1999 in order to determine the relative advantages of the two-phase pump solution (Charron, 2000). The program included thermodynamic characterisation at equilibrium conditions of a mixture including salted water, carbon dioxide, hydrogen sulphide and C_1 to C_5 alcanes (with mole fraction lower than 15%). The dissolution of a gas in a liquid is not instantaneous and, due to the relatively short transit time of mixture in a pump (shorter than one second), delay of gas dissolution during the compression must be considered to optimise the hydraulic design of the pump. This was achieved by the introduction of a kinetic factor in a thermodynamic module to allow for the calculation of thermodynamic properties (densities, mass and heat transfers) in conditions of partial dissolution.

The kinetic effect of gas dissolution was measured through out tests in a multiphase pump with various mixtures presenting different degrees of gas solubility. The tests aimed at establishing the delay in gas dissolution. They have shown a relatively significant effect of the kinetic of the dissolution for gas-liquid ratios in actual conditions (GLR) ranging between 3 and 10 (*i.e.* GVF ranging between 75% and 91%).

Even in the case where the dissolution of gas is low or nil inside a hydraulic cell, the compression of a sour gas-water mixture is feasible but an adaptation of two-phase pumping units to the conditions of production may be required to optimise the performance. For this purpose, several means have been studied, such as: stabilisation of the dissolution at an intermediate stage of compression; partial recycling of the liquid phase at the pump inlet, heat transfer (for instance, cooling of the two-phase mixture) or the use of a hybrid compression system (association of different types of hydraulic cells).

Economical studies have shown that the greatest the pump inlet pressure, the highest is the interest in using a two-phase pump in terms of absorbed power. In some cases, the two-phase pump absorbed power may even be smaller that the one absorbed by conventional units due to the simple effect of a mass transfer from the gas phase to the liquid phase during a two-phase compression.

3.2 Wet Gas Compressor

Early demonstrations of multiphase pumping started with GLR lower than 1 (volume throughput of the liquid higher than that of the gas) then the demand quickly exceeded this

(2) FPSO: floating production storage and offloading (floating production system based on a ship-shaped hull).

value. Nowadays, many operators wish to transport a two-phase mixture of which the GLR is considerably higher than 10 (of the order of 100 in some cases) by using two-phase flow units in view of reducing the production equipment (suppression of separation vessels, suction drums and transfer pumps). When the GLR is of the order of 100, the density of the mixture being relatively close to that of the gas, the compression ratio can only be achieved by using relatively high peripheral velocities. The limitation of erosion by liquid droplets at entry of hydraulics leads to design specific impeller geometry with an inlet diameter smaller than the outlet diameter, having some features of mixed-flow impellers.

3.3 Two-Phase Flow Turbine

The experience gained in the field of two-phase compression, operating on the rotodynamic principle, has lead *IFP* to investigate two-phase flow turbines operating on a similar process of energy transfer.

For operators, the use of two-phase turbines present similar advantages to those relative to single-phase turbines except that they are designed for two-phase flow applications:

– production of electricity in remote areas;
– additional production of liquid (with a greater commercial value than the gas) compared to a let down valve;
– cold production and temperature reduction with a two-phase compressible mixture.

If several types of two-phase turbines are already present on the market, these machines often operate in very specific conditions. For instance, turbo-expanders, largely used in gas liquefaction and drying processes are only designed for two-phase flow forming downstream the entrance of the hydraulics. In no case, they could accept a two-phase mixture at inlet considering the extremely high peripheral velocity (of the order of 400 m/s) and the risk of a rapid destruction of turbine internals by droplet erosion. Machines of the impulse type have appeared some years ago on the market. However, these machines are rather designed for the separation of gas and liquid phases with a potential for energy recovery. These machines are relatively bigger compared to helico-axial turbines, sensitive to rotor unbalance, also their efficiency may vary considerably with operating conditions.

The two-phase turbine presently being studied at *IFP* could accept any fraction of gas and liquid at inlet. They would be relatively compact while offering good hydraulic performance, in particular, when the liquid/gas density ratio is smaller than 100.

Several types of applications have been identified to-date. For upstream duties, foreseen applications include the replacement of choke valves by turbines, the replacement of let down valves by turbines in oil stabilisation units, the use of turbo-pumps in fractured reservoirs with both high and low pressure wells to increase the pressure of production, the use of two-phase turbines to reduce both the pressure and the temperature of high pressure and high temperature wells and also the production of energy in isolated areas (subsea or small platforms).

Downstream applications could include: the replacement of two-phase let-down valves (between condenser and evaporator) by turbines in refrigeration units to increase the cooling duty and reduce the compression duty, the replacement of Joule-Tompson valves by turbines in mixed coolant refrigerant circuits and in main gas liquefaction lines to increase the production of liquefied gas. The number of applications is very broad. One can still quote the use of turbines in a hydro-craking process for energy recovery and in a gas processing unit for recovery of condensates. In general, any two-phase let-down through a turbine in a fluid process (petrochemical, chemical, geothermal) can provide an increase in cooling duty, energy recovery and liquid recovery.

3.4 Two-Phase Flow Hydraulic Design

The design of two-phase hydraulics depends largely on the energy mode of transformation (compression or let-down), of the characteristics of the two-phase mixture (primarily, density and volume flow ratios), of thermodynamic properties (viscosity, volatility and solubility of the components), of the number of phases (presence of sand or emulsions) but also of external constraints (machine installed on the surface or inside a well).

An energy transfer from a fluid to the rotating shaft of a machine is not strictly the reverse of an energy transfer from a rotor to a fluid considering the numerous differences in flow behaviour, such as blade incidence and diffusion losses to quote only a few in single-phase flow. In addition, with two-phase mixtures, the gas plug causing a performance reduction in a compression process will present a totally different behaviour in a let-down process.

At low GLR and in the case of a viscous liquid, the analysis of a bubbly flow shows the importance of the drag forces compared to inertial forces leading to a shortening of impellers blades and also of their radius of curvature.

Conversely, with large GLR where the effect of the viscosity of the liquid phase becomes negligible, it is the displacement of a liquid film and questions related to erosion by liquid droplets that prevail considering that for these applications it is appropriate to use high peripheral velocity and semi radial shapes.

4 EXPERIMENTAL STUDY OF MULTIPHASE FLOWS

The increasing number of pumps operating in multiphase flows and their increasing power, lead to develop a specific research pump with a transparent body, used to investigate

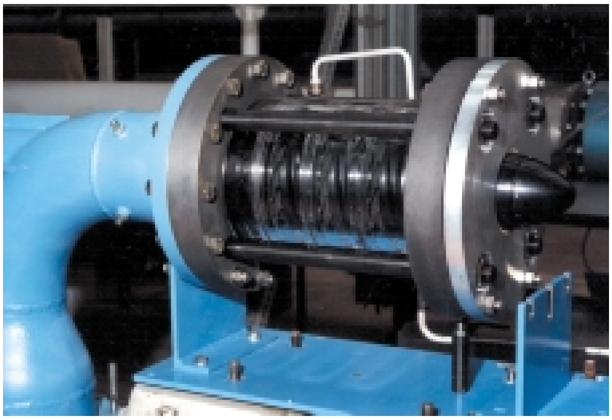

Figure 3

Research test pump.

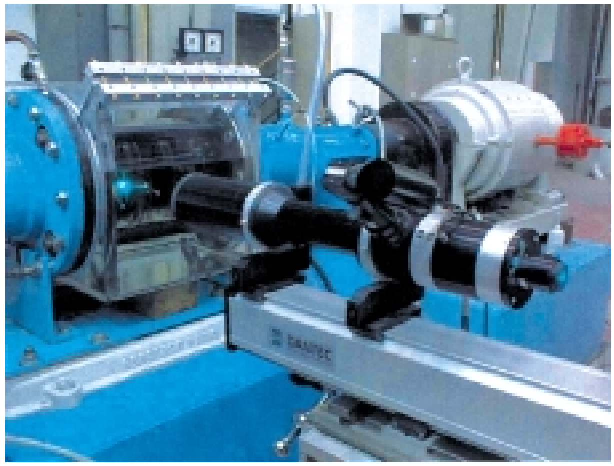

Figure 4

Laser Doppler anemometer.

and optimise the three dimensional flow inside the compression cells. This experimental set-up was used in a wide range of single phase and two phase bubbly flows with the purpose of detailed visualisation and understanding of the 3D flows through the pumps compression cells. The objective of the experimental work was to improve pump performance and to provide some experimental data to validate the results of numerical simulations.

The research pump, as shown in Figure 3, is equipped with a transparent shroud and can accept up to three hydraulic stages. The shroud was designed in order to allow a 360° visualisation of the flow and to make use of several sophisticated measurement techniques (laser Doppler anemometry, visualisations with a high speed camera and optical void fraction probes) with the aim to determine the velocity field of the flow, the size distribution of bubbles and the three dimensional space distribution of bubbles (El Hajem *et al.*, 2001).

The apparatus for velocity measurement with a laser Doppler anemometer (LDA) is shown in Figure 4. It consists in a 5 W laser source in multi spectrum lines mode in order to operate in the 488 nm wavelength and the 514.5 nm wavelength. The measurements are made in the back scatter mode with modular optics including a transmission lense to focus three beams and two photomultipliers for the reception of the signals diffused by calibrated particles injected into the flow. The beams are focused into a 1 mm size probe volume which can be moved easily form the hub to the shroud. Finally, the anemometer is associated with an optical encoder mounted on the pump shaft in order to synchronise the velocity measurements with the angular position of the impeller blades.

Velocity measurements have been performed by means of this data acquisition system inside 6 cross-sections of the flow from the inlet of the impeller to the outlet of the diffuser. Several pump speeds of rotation and flowrates were tested in order to assess the effect of the Reynolds number on the flow characteristics and to measure the flow at low relative flowrates (Vilagines *et al.*, 1995).

A example of measurement of the axial flow velocities in the inlet cross-section of the impeller and in the blade tip region, is showed in Figure 5. This result was obtained at the best efficiency point with a pump rotation speed of 1500 rpm. The effect of the leading edge of the four impeller's blades passing in front of the measurement volume is clearly shown on this figure. A statistical averaging was made on the velocity measurements of this type and the axial velocities fields in the cross sections at inlet, mid-span and outlet of the impeller were obtained with flows of single phase water.

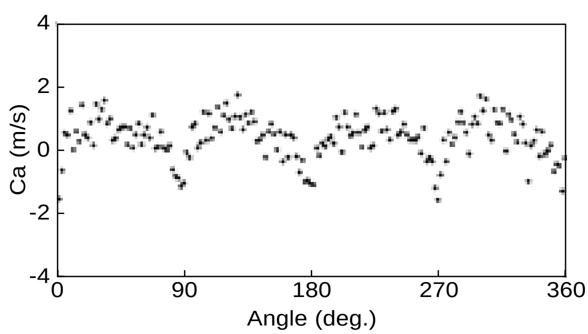

Figure 5

Example of results with LDA (blade tip section, impeller leading edge, best efficiency flowrate).

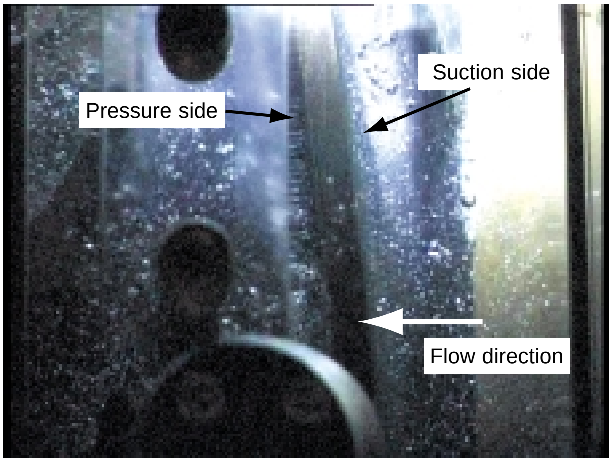

Figure 6

Dispersed bubbly flow in a compression cell.

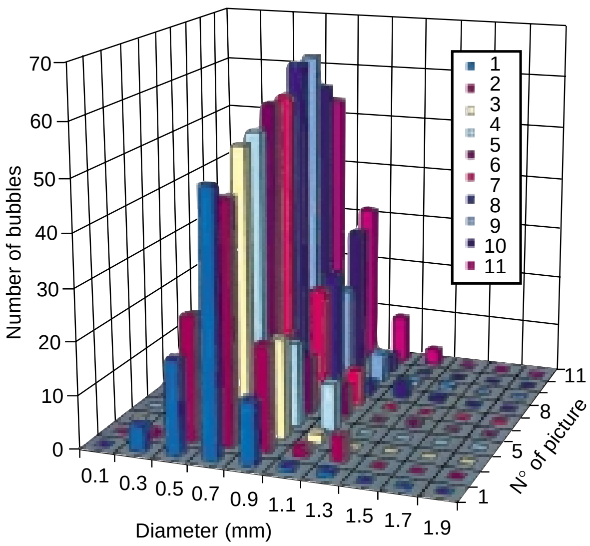

Figure 7

Size distribution of bubbles (mid-span, diffuser trailing edge, best efficiency flowrate).

The experimental data analysis and interpretation put in evidence some secondary flow regions, often observed within this type of pump geometry, like a flow recirculation located upstream of the leading edge of the impeller in the tip region. Also, some vortex structures due to tip clearance flows have been observed near the blades tip.

The visualisation of dispersed bubbly flows with a high speed camera, as shown in Figure 6, was used to estimate the size distribution and the velocity of the bubbles. Figure 7 represents the size distribution of bubbles, evaluated from a series of 11 successive pictures. These tests were done at the best efficient point, near the outlet of the diffuser, with a 10% gas volume fraction.

5 CFD ANALYSES OF HELICO-AXIAL HYDRAULICS

Until 1992, the R&D on helico-axial hydraulics was mainly based on an experimental approach completed by Euler single-phase flow simulations. Progress in flow simulation has considerably increased the role of computational fluid dynamics (CFD). The use of powerfull 3D Navier-Stokes flow solvers spread out for tubomachinery design during the last 10 years and especially at *IFP* for helico-axial hydraulics.

Analyses are generally performed in single-phase steady flow only, but few transient analyses and two-phase flow analyses have been carried out. Single-phase characteristic curves and efficiency curves derived from CFD agree relatively well with the experimental data with a slight tendency to over-predict flow rates. In order to obtain realistic results, inlet and outlet flow distributions must be input carefully and all loss sources must be modelled, especially friction and flow recirculation in clearance between fixed and rotating parts. A full stage must be modelled. Sometimes, two successive stages (2 rotors and 2 stators) are modelled to improve the accuracy of results.

Some 3D analyses have been done also in two-phase flow with the CFD software Fluent™, developed and marketed by the company *Fluent Inc.* The two-phase flow model selected for these analyses is an Eulerian model where the slip velocity of the dispersed phase is solved by a single mixture equation. The single two-phase flow variable is the volumetric fraction of the dispersed phase in the continuous phase. This model supposes that the volumetric fraction of the dispersed phase is not very high (10% maximum) and it neglects mass transfers between phases. Even with these strong limitations, such a model provides relevant information on the two-phase flow performance of the stage.

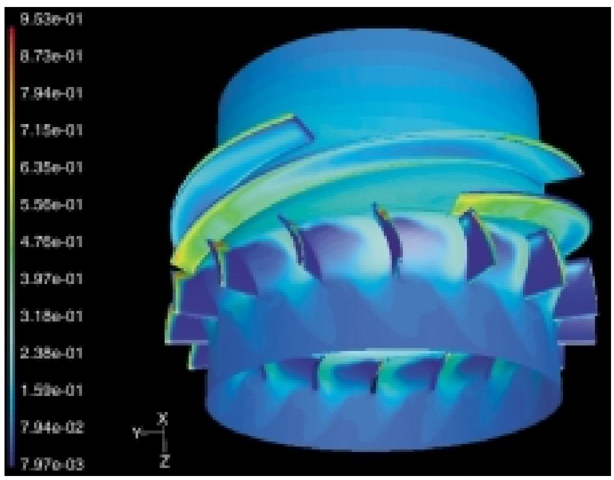

Figure 8

Calculated distribution of gas volumetric fraction (GVF) (inlet GVF: 5%, rotation speed: 3000 rpm, the GVF color scale range from 0 to 0.1).

A transient analysis is performed to solve the problem. Some gas (5%) is introduced at inlet as a homogeneous dispersed phase. Its concentration varies during the passage through out the hydraulic channels of a full stage, showing areas of preferential accumulation or rarefaction. For instance, in Figure 8 which shows a map of the calculated gas fraction, it can be seen that there is no gas at the leading edge of the impeller blade (because of the high positive pressure gradient), there is a thin area of gas concentration on the blade suction side and the opposite on the pressure side. The gradient of gas concentration decreases quickly as the flow moves toward the trailing edge. It is recalled that the hydraulic design of the cells aims at avoiding phase separation in the impeller. Similar observations may be done on the stator blades.

6 COMPUTERISED SHAPE OPTIMISATION

When considering the multiplicity of potential high-power applications (2MW and above), the availability of an efficient method for adjusting and optimising the compression cell shape becomes an issue of paramount importance to fulfill at best the customer needs.

Customary optimisation methods are based on the expertise of designers performing few iterations with a trial and error procedure. This conventional approach may be made faster and much more efficient by using the computerised optimisation methods developed in the recent years. These methods are based on the availability of efficient 3D Navier-Stokes (NS) solvers.

NS simulations still require large computational efforts and involve a large amount of data. In order to remain practically feasible, the optimisation method must limit the number of Navier-Stokes analyses. For this reason, many optimisation methods are impracticable, as the conjugate gradient optimisation method for instance. Some imitation of the human intelligent behaviour must be introduced in the procedure.

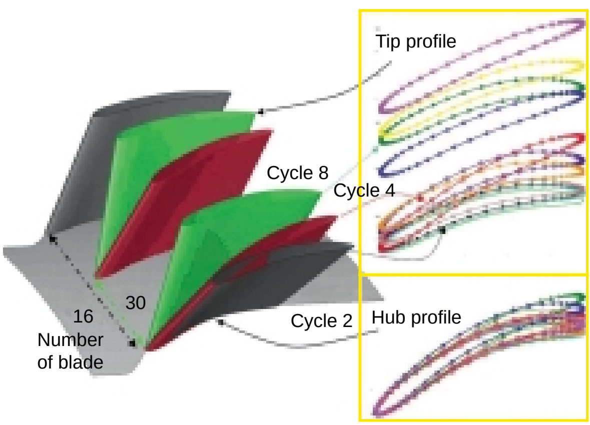

Figure 9

Evolution of blade shape during the optimisation steps.

The selected approach combines the use of an artificial neural network and a genetic optimisation algorithm. The neural network evaluates performance and enlarges a database composed of a limited number of Navier-Stokes analyses. As the optimisation moves on, successive NS calculations are only carried out on the most promising geometries in order to increase the accuracy of the database. The optimisation is achieved by minimising a “cost function” which includes penalty terms to constraint several specific features of the flow as the radial velocity distribution at inlet and outlet.

This approach has been implemented in collaboration with the *Von Karman Institute (VKI*) which provided the scientific background in genetic optimisation of radial turbomachines. The steps of the development include:

– a parametric definition of the compression cell shape (17 parameters), and the selection of relevant performance parameters (16);
– the coupling of a NS solver (currently TRAFM3D[3], in use at VKI) with an appropriate mesh generating interface;
– the building of an initial database of 20 NS analyses on different shapes;
– the development of the artificial neural network and the genetic optimisation algorithm.

This optimisation procedure is presently operational in single-phase flow *(Fig. 9)*. The coupling with other CFD codes currently in use at IFP will be completed next year. The introduction of some type of analysis in multiphase flow, more or less simplified, must also be introduced to converge towards an optimized shape in multiphase flow.

CONCLUSIONS

Helico-axial multiphase pumps are now state-of-the-art technology and receive a widespread acceptance from the oil operators. They can suit a great number of application cases and a broad range of operating conditions. They enable new options for field developments, both onshore and subsea, and they are well adapted to large flowrates or subsea applications. They offer significant economical advantages and operational flexibility for the operator. The production of very large fields relies now on this technology.

New potential applications are currently under development at *IFP*. These developments make use of the most advanced experimental and computational techniques in order to offer at best, innovative and efficient products to the oil industry.

(3) TRAFM3D™, is a CFD software developed by *NASA* and the University of Florence.

ACKNOWLEDGEMENTS

The authors wish to thank Professor R.A. Van den Braembussche *(VKI)*, Professor R. Morel and Prof. J.Y. Champagne *(INSA-Lyon)*, Olivier Tuot, Mahmoud El Hajem and Charlotte Ozenne for their contribution to the R&D works presented in this paper. They thank also their retired colleague Henri Cholet for providing Figure 1.

REFERENCES

Arnaudeau, M. (1988) Development of a Two-Phase Oil Pumping System for Evacuating Subsea Production Without Processing. *20th Offshore Technology Conference*, Paper 5648, Houston, May.

Charron, Y. (2000) Simultaneous Reinjection of Sour Gas and Water with a Multiphase Flow Pump. *European Association of Geoscientists and Engineers Conference*, Glasgow, May 29-June 2.

El Hajem, M., Morel, R., Champagne, J., Vilagines, R. and Pagnier, P. (2001) Exploration par anémométrie laser Doppler de l'écoulement dans une pompe hélico-axiale. *La houille blanche*, n° 3/4.

Engelman, E. and Torp, T.A. (1990) The Poseidon Project and the Future of Multiphase Production. *Offshore Northern Seas Conference*, Stavanger.

Falcimaigne, J. (1992) Multiphase Flow: Cost-Efficient Solution for Marginal Field Developments. *European Petroleum Conference - EUROPEC 1992*, Paper 25064, Cannes, November.

Falcimaigne, J., Durando, P., Loupias, M. and Vilagines, R. (1994) Multiphase Rotodynamic Pumps Extend their Operating Capabilities. *European Petroleum Conference - EUROPEC 1994*, Paper SPE 28882, London, October 25-27.

Gié, P. (1991) The Poseidon Project: 1990-1991 Achievements. *6th Deep Offshore Technology Conference*, Monaco, November 4-6.

Heintzé, E., de Salis, J. and Charron, Y. (1999) Dynamic Simulation of Multiphase Flow Pumps. *Multiphase 99 Conference*, Cannes.

Korolov, S.V., de Salis, J. and Birnov, M.A. (1999) Oil Field Development in Western Siberia: a Multiphase Pump Case Study. *Multiphase 99 Conference*, Cannes.

Leporcher, E. and Taiani, S. (1995) Multiphase Pumping: the Lessons of Long-Term Field Testing. *SPE Annual Technical Conference*, Paper 30661, Dallas, October 22-25.

Leporcher, E., Delaytermoz, A., Renault, J.F. and Gerbier, A. (2001) Deployment of Multiphase Pumps on a North Sea Field. *SPE Annual Technical Conference*, Paper 71536, New Orleans, September 30-October 3.

Longworth, H.L., Dun, G.C. and Semchuck, M. (1996) Underground Disposal of Acid Gas in Alberta, Canada: Regulatory Concerns and Case Histories. *SPE Gas Technology Conference*, Paper 35584, Calgary, April 26-May 1.

Pershukov, V.A., de Salis, J. and Cordner, M. (2001) Multiphase Pumps for 250 000 bbl/d Field Development. *SPE Annual Technical Conference*, Paper 71562, New Orleans, September 30-October 3.

Skiftesvik, P. and Sværen, J. (2000) Application and Status of New Building Blocks for Subsea Boosting and Processing Systems. *2000 Offshore Technology Conference*, Paper 12016, Houston, May 1-4.

Vangen, G., Carstensen, C. and Bakken, L.E. (1995) Gullfaks Multiphase Booster Project. *27th Offshore Technology Conference*, Paper 7930, Houston, May 1-4.

Vilagines, R., Spettel, F., Morel, R. and Hidra, M. (1995) Experimental Study of Unsteady Wall Static Pressures in a Multistage Pump. *Second Int. Conference on Pumps and Fans*, Beijing, October 17-20.

Final manuscript received in October 2001