SPE 63039

Design and Analysis of a Multiphase Turbine for Compact Gas-Liquid Separation

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This paper was prepared for presentation at the 2000 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, 1–4 October 2000.

Abstract

The Rotary Separator Turbine (RST) utilizes unique technology to provide compact separation of oil and gas, while recovering energy wasted in conventional pressure let-down operations. The technology has been utilized for industrial refrigeration and geothermal applications since the early 1980's, and has recently finished field evaluation and assessment on a deepwater tension leg platform in the Gulf of Mexico. The focus of this paper is on the operating principles and mechanisms of multiphase turbine technology and design parameters for installation as a separation or power generation system in new developments or in debottlenecking applications. Operational experience pertaining to separation efficiency, mechanical reliability, and power output in a live fluid environment will be highlighted.

Introduction

Conventional technology for separation of liquids and gases is well developed in the petroleum industry. Reliable separation technologies based on gravity settling, have been available for many years. However, the changing economics of oil and gas production, deriving from fields with smaller recoverable reserves and/or deepwater environment, require improvement over the methods currently used to reduce the cost of development and operation.

The large footprint and weight characteristics of conventional gravity based separators require substantial support structure when used offshore and are expensive to transport and install. Additionally, the energy available in the high-pressure multiphase fluids that are treated by these separators can be significant. Current oil and gas separation systems waste this available energy through dissipation as pressure drop across a choke or other reduction valves. Recovery of this energy, in whole or part can offset power generation cost and is free from greenhouse emissions.

The RST provides compact and efficient gas-liquid separation while recovering the pressure drop energy. This energy can be put to use for liquid pressurization, shaft power, or a combination of the two. Separation efficiency of the gas and liquid meets or exceeds that of a conventional vessel separator, with only 25% of the weight or volume. Additional benefits of the RST stemming from the centrifugal separation include foam reduction and improvement in operability due to motion insensitivity.

Rotary Separator Turbine

The RST is an outgrowth of high velocity two-phase flow research at the Jet Propulsion Laboratory[1]. Extensive experimentation on two-phase nozzles, and experience with stationary separators and two-phase diffusers, established the technical foundations for rotary separator turbines. The first turbines were tested in 1974 with compressed air and water at the 2 kW level. Subsequent demonstration turbines, designed and tested for geothermal power applications, operated on brine and steam. These demonstration units ranged from a 30" (750 mm) turbine operating at 21 kW in 1979, to a 54" (1,350 mm) turbine operating at 1569 kW at Roosevelt Hot Springs, Utah in 1983. The larger unit was operated for a 4000 hour reliability test and exhibited 100% mechanical availability and no erosion.

Simplification of the rotor design and addition of gas blading was introduced, and a new design sub-scale prototype was tested at Coso Hot Springs, California in 1993. This unit operated for 700 hours at 42 kW with no measurable erosion. As a result, a full size commercial unit was installed in August 1998 at Cerro Prieto, Mexico for a commercial demonstration project. The 30" (750 mm) diameter commercial unit was designed for a power output of 2 MW.

The first oil and gas application involved the use of the RST as a centrifugal foam breaker for an offshore application. An aqueous foamy mixture (beer) was successfully tested in a lab unit and recycled by the test crew. A reaction type sub-scale RST was built and operated with natural gas and foamy crude at a gas plant. Complete foam breakdown was observed resulting in a liquid carryover of only 30 PPM. A full commercial prototype was manufactured in 1984 for 100,000 BPD flow at 1000 psia inlet pressure; however because of changes in the target test site the unit was never placed in service.

Further test work was done in 1996 using a drag RST for separation of inert gases and crude oil during offshore loading. This unit was short term tested in a pilot plant on an oil tanker in the North Sea. The unit exhibited good separation and performance was unaffected by the ship's motion. A Joint Industry Program was formed in 1997 to test a second RST at a major oil and gas test facility.

Rotary separator turbines have been installed in waste heat recovery applications and have enjoyed commercial success in industrial refrigeration applications. More than 100 commercial chillers (up to 2,500 tons) are operating with rotary separator turbines.

Operating Principle/Components

The basic principle of operation and the liquid and gas flow path are shown in **Fig. 1**. The four main components of a rotary separator turbine are[2];

- Two-phase nozzle, to convert fluid pressure into a high velocity homogenous stream
- Rotor drum for separation and energy transfer
- Diffuser scoop or reaction jets for liquid extraction
- Gas blading for power extraction

Two-Phase Nozzles

Conversion of the two-phase pressure energy to kinetic energy is accomplished by accelerating the gas-liquid mixture through inlet nozzles that are essentially "Laval" type nozzles. The shear intensity in the expansion nozzle is considerably less than that generated in a pressure let-down valve. Consequently the tendency for foam and emulsion formation is significantly reduced. Jet flow characteristics such as spouting velocity, gas and liquid mass fractions, droplet size, temperature, density, and viscosity are calculated by a computer code. The code is integrated with a process simulation toolkit (HYSYS) for calculation of thermodynamic expansion for hydrocarbon mixtures. The code also calculates the ideal nozzle geometry based on a set of process parameters. For final design purposes it is necessary to use the code, but experience reveals that often not all of the necessary input information is available during early stage estimation. An approximation can be obtained by applying an energy balance for isentropic expansion:

$$h+½v^2=\text{constant, where } h=(1-x)h_l+xh_g \quad (1)$$

The velocity is given by:

$$v_{ei}=[v_0^2+2(h_0-h_{ei})]^{½} \quad (2)$$

Since the expansion is only partially isentropic, the actual velocity is given by:

$$v_a^2=\eta_n v_{ei}^2 \quad (3)$$

The isentropic efficiency of the nozzle ranges from 0.7 to 0.95 depending on pressure, pressure ratio, and surface tension.

Because of density difference the gas phase accelerates more rapidly than the liquid. Shear forces exerted by the higher velocity gas will break up the liquid into smaller droplets. In turn, the smaller droplets have a larger surface area to mass ratio. This facilitates a more efficient momentum transfer between the liquid and the gas during the pressure decline, resulting in an even distribution of fine liquid droplets suspended in the continuous gas phase of the exit jet.

A rotary separator turbine contains several inlet nozzles spaced around the rotor circumference to distribute the flow evenly. The two-phase jets are impinged near-tangentially onto the inner surface of a rotating cylindrical rotor. The liquid rapidly disengages from the gas and forms a layer on the rotor rim which to some extent, protects it from possible erosion. The gas forms a free vortex at a smaller radius than the rotating liquid layer.

Separator Drum

Power transfer by liquid drag takes place when the liquid from the inlet jets is slowed down to the rotor rim speed by viscous coupling. The centrifugal field generated by the rotating drum, 2000-4000 times the force of gravity, forces rapid separation of the gas and liquid, breaks foam structures, and aids oil droplet coalescence. The rotor itself is slowed below the free rotation speed to a fixed speed by coupling the turbine to a generator, pump, compressor, or water brake. A schematic of this mechanism is shown in **Fig. 2**.

The total available energy for drag power transfer is represented by:

$$P_{tot}=m_l[(v_{tan}^2-\omega r_2)/2)] \quad (4)$$

The power actually generated is given by:

$$P_{drag}=m_l(v_{tan}-\omega r_2)(\omega r_2) \quad (5)$$

Therefore the efficiency is:

$$\eta_{drag}=(2\omega r_2)/(v_{tan}+\omega r_2) \quad (6)$$

and

$$P_{drag}=\eta_{drag}P_{tot} \quad (7)$$

Gas Blading

The kinetic energy of the separated gas can be recovered as shaft power by using blades as shown in **Fig. 1**. The amount of power recovered from the gas phase is represented by:

$$P_g=½m_g\eta_g v_{tan}^2 \quad (8)$$

The gas blading efficiency normally ranges from 0.70-0.85, depending on the specific speed and diameter of the turbine. The blade type best suited for this type of turbine is impulse blading, whereby the pressure drop is kept at a minimum. With this blade type, the ratio between absolute blade velocity and incoming gas velocity ranges from 0.45-0.55.

Liquid Reaction Jets

To maximize shaft output while still providing substantial gas-liquid separation, reaction jets can be added to the RST. The basic purpose of the reaction jet is to extract useful work from the rotating separator drum liquid. The high static head produced from the centrifugal force field is used to accelerate the discharged liquid in a direction opposite the rotational motion. This relative velocity reduces the value of the absolute velocity of the liquid leaving the rotor. The two advantages to this design are to add to shaft torque and minimize the impact velocity of the liquid jet on the surrounding casing. These factors respectively add to the power recovery and minimize erosion potential.

Power recovery from the reaction jet is determined by the Euler equation:

$$P_{reaction}=m_l(c_2u_2-c_3u_3) \qquad (9)$$

The entrance and exit of the reaction nozzle channel is shown in **Fig. 3**.

Reaction jets are not part of all turbine designs, because it is sometimes more beneficial to evacuate the liquids from the rotor by using a diffuser scoop arrangement.

Diffuser Scoop

The separating turbine uses a diffuser scoop for liquid removal to pressurize the liquid and to prevent gas carry-under. This type of turbine can be employed for two- or three-phase separation. The diffuser scoop is able to remove liquid from the rotor and convert the kinetic energy of the rotating fluid into pressure by the controlled reduction of velocity. The scoop is fully or partially immersed in the liquid layer on the rotating rim, as shown in **Fig. 4**.

Significant research has been undertaken on the diffuser scoop. The duty of this device is significant because it must maintain a nearly constant liquid layer during variations in liquid flow rate, while minimizing gas entrainment in the discharged liquid. The scoop also must be designed to keep the wake spray at a minimum, becasue such spray may result in liquid carryover to the gas discharge from the turbine.

As shown in **Fig. 4**, a gas barrier can be employed to prevent gas from reporting through the liquid outlet. The barrier is held in place by balancing the downward force, provided by an actuator or spring, with the inertial forces from the liquid passing under its flow surface. The primary advantage of the diffuser inlet barrier is self-compensating action over wide variations in liquid flow rates.

Power Recovery

The power recovery type turbine is oriented to maximize power output by using gas blading and reaction jets. The power recovery turbine design can obtain significant power from high pressure, high temperature (HP/HT) gas/condensate wells. Current designs indicate that units are capable of generating 10 MW of electricity for the duration of field life.

To maximize power recovery, the pressure drop in the upstream choke valves can be shifted to the separating turbine. This has received special attention in the Norwegian sector of the North Sea where the cost of operating hydrocarbon-fueled generator sets is driven up by the taxation on CO_2 emissions. There also have been several significant HP/HT reservoir discoveries for which this technology may be applied. It also can be used in remote locations where the cost or weight of providing remote power is excessive. In the case of a high pressure field where there is also a high gas to oil ratio, a power recovery turbine may be able to replace the second stage separator while producing a significant amount of power.

Useful work from the output shaft can be used to drive a compressor, transfer pump, or other rotating-type device. Scenarios have been designed to use a power recovery turbine at the high pressure (HP) stage of a multi-stage separation facility, with the output power used to drive a three-phase separating turbine on the low pressure (LP) stage. A direct coupled design of this type fully captures the power and separation potential of this technology.

Two-Phase Oil-Gas Separation

A typical separator turbine will exhibit an actual liquid residence time of 0.5-1.0 seconds. Coupled with the centrifugal force imposed on the liquid layer of several thousand times the gravitational force, the equivalent residence time is 30-60 minutes. It is the long, effective residence time that provides efficient separation of the phases and compact equipment dimensions.

While a separating turbine may be capable of shaft power output, most applications will be designed so that the expansion power provided by the nozzles will approximately balance the power consumed by the unit, simplifying package design. Power generation would be added only if there is a significant power generation potential to justify the additional cost of generator switchgear and controls. A starter motor may be connected to the shaft for start-up and speed control.

The separation turbine will typically be suited for operation on wells with high volumes of associated gas. Liquid removal from the rotor would normally be effected using a diffuser.

Flow Loop Testing

A two-phase rotary separator turbine was designed and manufactured to demonstrate operation with oil, gas, and water as part of a Joint Industry Project (JIP) involving nine oil companies[4]. The turbine was installed and tested for 15 days during the early summer of 1998 at the Texaco Humble Flow Test Facility in Humble, Texas.

The RST was designed with a 24” (600 mm) rotor and built to ASME 600# equivalent rating. This unit has nameplate capacity of 20,000 BPD (132.5 m^3/h) liquid and 20 MMSCFD (23,600 Sm^3/h) gas. The design pressure drop was 225 psi (15.5 bar). A section view of the unit is shown in **Fig. 5**.

Efficient separation of gas and liquid was the primary parameter tested. The exhibited separation efficiency was >99.4% over a wide range of mass flow, GOR, water cut, temperature, and rotational speed.

The pressure recovery potential of the liquid diffuser was also demonstrated at the highest liquid flow rate in the test program. At 10,300 BPD (68.2 m^3/h) liquid flow rate, a stable discharge pressure of 438 psig (30.2 bar) above the turbine separation pressure was recorded. This was 293 psig (20.2 bar) above the turbine inlet pressure.

Throughout the test period the turbine was easily controlled with low vibration and noise levels. The wide range of operating conditions from the test matrix was easily accommodated.

Power recovery from the separation process was monitored throughout the test program and found to be much less than predicted. Two possible sources of unanticipated power loss were identified. First, upon commencement of the test program it was found that the test loop was only capable of providing about one-half the unit nameplate capacity as a two-phase stream. Second, the mechanical shaft seals exhibited significantly higher power consumption than indicated by the manufacturer, resulting in high parasitic losses. A power output of 15 kW was measured, compared to the 150 kW predicted.

Offshore Installation

Full justification of the benefits of the RST required evaluation in a live oil producing environment. A host site was found on a major operator's deepwater tension leg platform (TLP) production facility located in the Gulf of Mexico.

The main goal identified for a field evaluation test was to have the RST package operate reliably in a live well environment for an extended period. This type of test would provide validation of separation and energy recovery capabilities. A flexible control system would also be tested and could be applied to other multiphase turbines, including the future Three Phase Rotary Separator (TPRS).

The flow loop validated unit was redesigned to suit the offshore production conditions on the TLP. The main design requirements were that the package had to be completely self-contained and not connected to the main platform's power grid while in operation. Output shaft power, while quantified, was dissipated via a hydraulic brake. The installed package was designed with a full-flow bypass which allows the well flow to be directed through the package, ensuring that no process shut-downs would occur. The unit was removed from the flow facility and was modified for the long field evaluation program. Modifications to the unit included correcting the seal losses, adding impulse-type blading for the gas path, and modifying the diffuser arrangement to reduce the spray carryover effects.

The package, shown in **Fig. 6**, is completely self-contained, and includes an on-skid PLC system which allows control and monitoring of the package during operation. The turbine is connected to a reducer gearbox that drives a hydraulic loop system used to dissipate excess shaft energy as heat. The package is complete with seal and bearing support systems, and an energy monitoring system for turbine shaft power and torque. A gas filter-coalescer is employed to monitor liquid carryover and a density meter is used to monitor gas carry under. Direct measurement of the gas carry under is also taken with a high pressure sample bottle. All data from the package is monitored continuously, and stored in a computer directly connected to the PLC.

The RST package will be installed to operate in series, upstream of the intermediate pressure (IP) separator. Raw well fluids will be directed to the skid, where the gas-liquid separation will occur. The separated fluids are measured, recombined, and discharged to the IP separator. At the time of writing this paper, the skid package was being installed on the platform.

Nomenclature

c_2 = *liquid velocity at reaction nozzle entrance, L/t, m/s*
c_3 = *liquid velocity at reaction nozzle exit, L/t, m/s*
h = *two-phase enthalpy, L^2/t^2, J/kg*
h_g = *gas enthalpy, L^2/t^2, J/kg*
h_{ei} = *exit mass enthalpy for isentropic expansion from inlet to exit conditions, L^2/t^2, J/kg*
h_l = *liquid enthalpy, L^2/t^2, J/kg*
h_0 = *inlet mass enthalpy, L^2/t^2, J/kg*
m_g = *gas mass flow rate, M/t, kg/s*
m_{ge} = *exit gas mass flow rate, M/t, lb/s*
m_{gm} = *mean gas flow rate, M/t, lb/s*
m_{g0} = *inlet gas mass flow rate, M/t, lb/s*
m_l = *liquid mass flow rate, M/t, kg/s*
m_{le} = *exit liquid mass flow rate, M/t, lb/s*
m_{l0} = *inlet liquid mass flow rate, M/t, lb/s*
P = *shaft power, ML^2/t^3, kW*
P_{drag} = *power produced from liquid drag, ML^2/t^3, kW*
P_g = *power recovered from gas phase, ML^2/t^3, kW*
P_o = *non-dimensional power factor*
$P_{reaction}$ = *power recovered from reaction nozzles, ML^2/t^3, kW*
P_{tot} = *total power from drag transfer, ML^2/t^3, kW*
r_m = *liquid to gas mass ratio*
r_1 = *liquid film surface radius of curvature, L, m*
r_2 = *rotor surface radius of curvature, L, m*
T_m = *inlet to exit mean temperature, T, °R*
u_2 = *rotor velocity at reaction nozzle entrance, L/t, m/s*
u_3 = *rotor velocity at reaction nozzle exit, L/t, m/s*
v = *velocity, L/t, m/s*
v_a = *actual velocity for nozzle flow, L/t, m/s*
v_{ei} = *true isentropic expansion exit velocity for nozzle flow, L/t, m/s*
v_{tan} = *component of v_a tangential to rotary motion at r_1, L/t, m/s*
v_0 = *nozzle inlet velocity, L/t, m/s*
W_{gm} = *exit gas molecular weight*
x = *mass fraction of gas in total flow*
Z = *gas compressibility factor*
h_{drag} = *efficiency of drag power transfer*
h_g = *efficiency of gas blading*
h_n = *isentropic efficiency of inlet nozzle*
w = *angular velocity of rotor, L/t, rad/s*

Acknowledgments

The authors wish to thank Kvaerner Process Systems and Multiphase Power and Processing Technologies for the opportunity to present this information. Special thanks are also extended to Keith Oxley (Shell Deepwater Services Inc.) Phil Bohlmann (Shell Exploration and Production Company) and Allan Budvitis (Shell Exploration and Production

Company) for their feedback and insight with respect to RST technology. Last but not least, we are indebted to the crew and management of the deepwater production facility where the offshore trial occurred for their vision in testing the RST skid package.

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Appendix – Power Estimation for Two Phase RST

The power output from a two-phase RST is estimated using the curves shown in **Fig. 7**[5]. All quantities are based on the average conditions for a two-phase expansion. The curves are calculated using the isentropic nozzle and turbine equations with typical efficiency and geometric factors.

In general, the curves should predict power for expansions from pressures above 400 psia to within ±10%. For inlet pressures below 400 psia, the power should be reduced by 5%.

To illustrate the application, an expansion from the Texaco-Humble flow facility is analyzed with nozzle and turbine computer code (HYPNOZ) and compared with the estimated calculations.

The known parameters are shown in **Table 1**. The liquid to gas mass ratio is given by:

$$r_m = (m_{l0} + m_{le})/(m_{g0} + m_{ge}) = 1.728 \quad \text{(A-1)}$$

and the pressure ratio is 1.920. The mean gas flow rate is 13.40 lb/s, and the mean temperature is 566.84 °R. Assuming no change in gas molecular weight through the turbine, results in a mean molecular weight of 19.47.

Based on the curve in **Fig. 7**, the non-dimensional power factor is approximately 0.27. The power is calculated by:

$$P = P_o(2.095)ZT_m m_{gm}/W_{gm} = 211 \text{ kW} \quad \text{(A-2)}$$

Results from the computer code show a power output of 209.6 kW, providing agreement with the estimation results.

The validity of estimation will be influenced by changes in nozzle efficiency, gas blade efficiency, geometric loss factors, and windage losses. The codes always should be used for final turbine design and accurate performance determination. However; this method can be used to estimate the power output and suitability of the rotary separator turbine for many oil and gas applications.

TABLE 1-DATA FOR CALCULATION EXAMPLE		
Inlet pressure	p_0	430 psia
Inlet liquid mass flow rate	m_{lo}	23.28 lb/s
Inlet gas mass flow rate	m_{go}	13.28 lb/s
Inlet temperature	T_0	580 °R
Gas molecular weight	$W_{go} \approx W_{ge}$	19.4662
Exit pressure	p_e	224 psia
Exit liquid mass flow rate	m_{le}	23.04 lb/s
Exit gas mass flow rate	m_{ge}	13.52 lb/s
Exit temperature	T_e	553.67 °R
Gas compressibility factor	Z	0.957

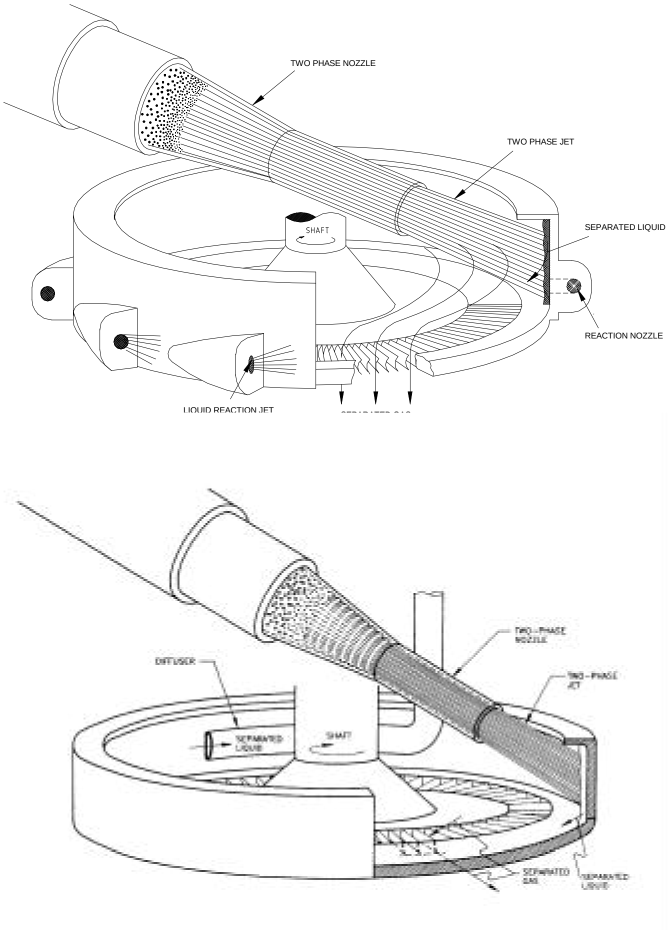

Fig. 1-Flow path and component diagrams of reaction type (top) and diffuser scoop type (bottom) rotary separator turbines.

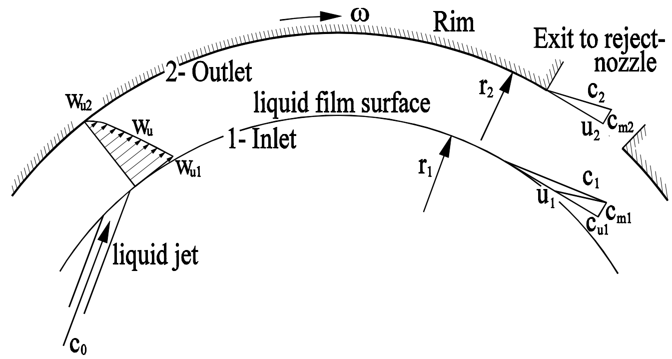

Fig. 2-Sketch of liquid layer on surface of rotating rotor surface.

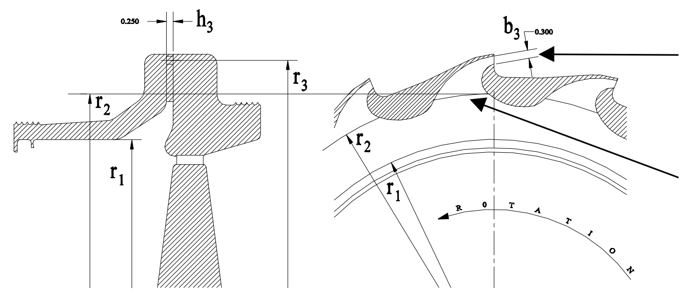

Fig. 3-Reaction nozzle layout on periphery of rotor.

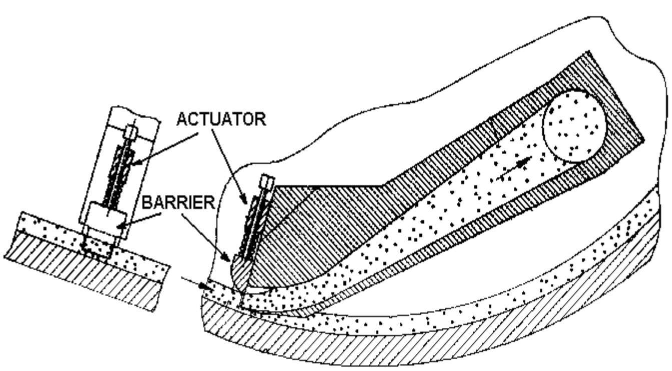

Fig. 4-Schematic of diffuser scoop with entrance barrier to prevent gas entrainment.

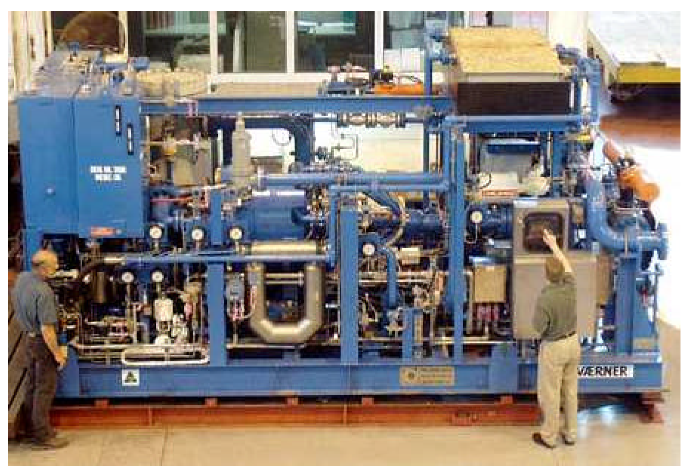

Fig. 6-Photograph off 24 RST skid package for offshore evaluation program.

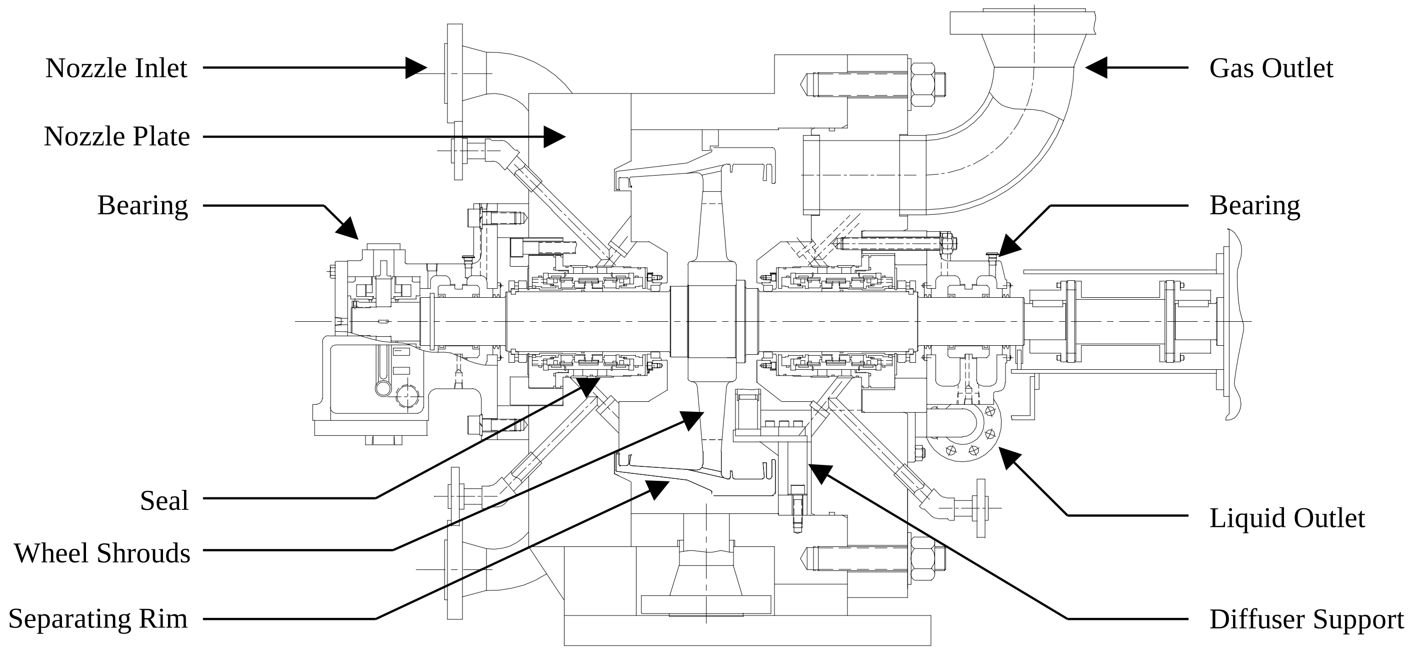

Fig. 5-Section view of Joint Industry Project test turbine.

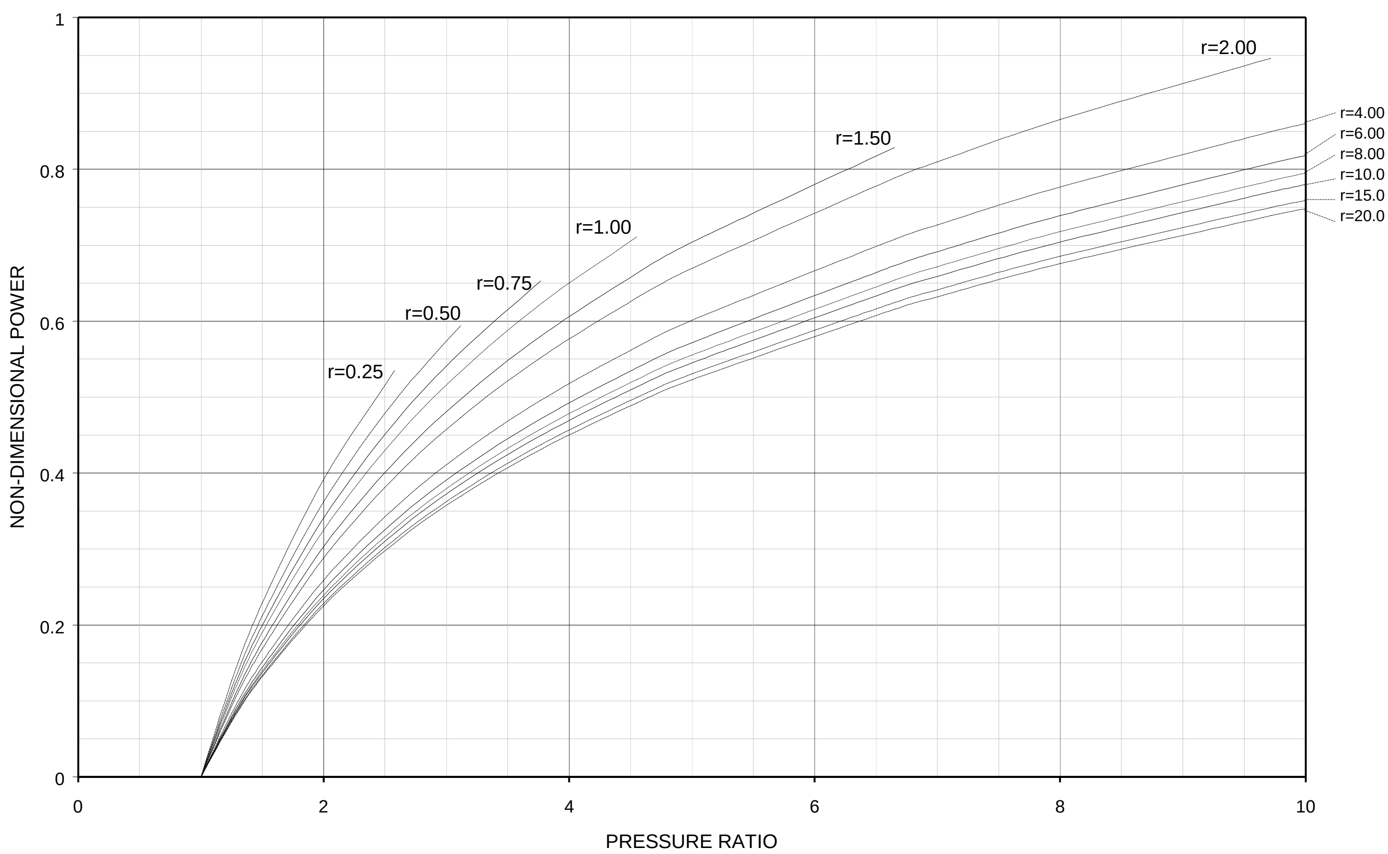

Fig. 7-Power versus pressure ratio, for varying liquid to gas mass ratios, for rotary separator turbines.