APPLICATION OF AN INFLOW RADIAL TURBINE IN A GEOTHERMAL ORGANIC RANKINE CYCLE POWER PLANT

Reza Agahi

Marketing Manager, Atlas Copco Gas and Process, 119 Mosaic, Irvine, California, 92603 USA

reza.agahi@us.atlascopco.com

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ABSTRACT

Inflow radial turbines, expanders and turboexpanders were first developed in the early 1930s. The first industrial application followed in the years 1934/35 in an air separation process. From the 1950s onwards, expanders were utilized in cryogenic plants for natural gas processing.

In the early 1980s, the Mammoth Lakes geothermal plant in California, USA, became the first large-scale geothermal Organic Rankine Cycle (ORC) plant to utilize expanders in an ORC cycle. The successful implementation of expanders in the Mammoth Lakes project led to another successful and even larger geothermal ORC plant with turboexpanders: the Steam Boat plant in Nevada, USA, in the early 1990s. Since then, many other large-scale geothermal ORC plants have installed radial inflow turbines throughout the world.

Turboexpanders have several unique design features that are ideal for applications in geothermal ORC plants. The inflow radial expander is a variable geometry turbine able to cope with the types of variations inherent to any geothermal power plant. A turboexpander with variable Inlet Guide Vanes (IGV) is perfectly suited to handle geothermal resource flow or temperature fluctuations in an efficient manner. Furthermore, daily or seasonal variations in ambient temperature can be managed with high efficiency in an ORC plant equipped with an inflow radial turbine. Temperature variations, in particular, are a major issue and can result in poor performance in other types of turbines, including axial turbines.

This presentation covers the basic design, unique features and performance parameters of radial inflow turbines in geothermal ORC plants. We also provide the comparative results from a simulation study for cumulative annual electricity production by an axial and radial turbine.

1. INTRODUCTION

1.1 History

The concept of an expansion engine dates back to the year 1900, when George Claude invented a piston expansion engine utilizing pistons in a cryogenic process to liquefy air (Kerry, 2007). Since then, several different types of turbines have been developed. Today, the most widely used turbines are axial turbines, radial inflow turbines and radial outflow turbine.

Radial inflow expansion turbines were developed in the 1930s and utilized in cryogenic processes for the air separation and industrial gas industries (Almqvist, 2002). Meanwhile, applications of expansion turbines in cryogenic processes in the natural gas industry only started in the early 1960s. Dr. Judson S. Swearingen modified and enhanced an existing inflow expansion turbine design to be suitable for hydrocarbon gas components and processing between 1959 and 1961 (Orbits, 1999). The first expansion turbine with compressor load was installed in a natural gas plant in Corpus Christi, Texas, USA (Orbits, 1999). Together with his company, Rotoflow Corporation, Dr. Swearingen focused on the development of inflow expansion turbines and their applications in the natural gas and petrochemical industries for more than 30 years (Bloch, 2001).

The name “expander” or “turboexpander” was coined by Dr. Swearingen to refer to an inflow radial expansion turbine.

1.2 Turboexpanders for Energy Recovery

A turboexpander extracts energy from fluid and thereby reduces fluid temperature at discharge. Expansion through a turboexpander is an isentropic process and more thermally efficient than free expansion; an isenthalpic process (Bloch, 2001).

Process designers for the industrial gases, natural gas and petrochemical industries are interested in utilizing turboexpanders because of their high thermal efficiency when producing refrigeration. In order to cool down, a turboexpander needs to extract energy from the process fluid. Harnessing this extracted energy is not the focus of those industries, but utilizing the energy is a logical step because it is available. Applications of turboexpanders for the explicit purpose of energy recovery did not arrive until the early 1970s.

The first energy recovery applications of turboexpanders were implemented in the pulp industry. A multi-stage turboexpander was designed to recover energy from waste heat through the expansion of hot exhaust flue gas from a paper factory (Aghai, 1975). Turboexpanders were also utilized for energy recovery in an Ocean Thermal Expansion Conversion (OTEC) project in Hawaii, USA, in 1979 (Meyer, 2007). Energy recovery from natural gas pressure let-down was also realized with a turboexpander in 1983 (Rheuban, 2009).

1.3 Turboexpanders in Geothermal Energy Recovery

Geothermal energy recovery for electric power generation has been in use for over 100 years. High enthalpy geothermal resources produce steam suitable for direct expansion through a condensing steam turbine. This is a common practice in so-called “flash” plants.

Some geothermal flash plants have utilized turboexpanders as back pressure turbines, placed upstream of a conventional condensing steam turbine. This configuration, when feasible, could result in substantial improvements in the efficiency of the energy recovery process (Hoyer, 1991).

Most geothermal resources worldwide are in the medium to low enthalpy category. Electrical energy recovery from these lower temperature resources can be achieved by utilizing an Organic Rankine Cycle (ORC). One of the pioneering applications of a high-power inflow radial turbine expander in an ORC system was implemented in Mammoth Lakes, California, USA, in 1984 (Holt, 1984).

The Mammoth Lakes geothermal ORC plant was unique in many ways: It was the first large-capacity plant to use iso-butane as the working fluid in the Organic Rankine Cycle. It was also the first large-scale ORC plant to utilize turboexpanders with variable Inlet Guide Vanes (IGV). Successful operation of the ORC plant at the Mammoth Lakes geothermal was also the motivation to expand the facility in 1989.

The Steamboat Springs geothermal project in Nevada[1'] USA, utilized the experience from the successful Mammoth Lakes plant. The Steamboat Springs plant was configured with four trains of turboexpanders with variable IGV and nominal power of 12 MW each (Agahi, 1997).

Details of process conditions, availability and reliability of both the Mammoth Lakes and Steamboat plant have been discussed and presented in detail by others (Agahi, 1997).

More recent geothermal ORC projects will be discussed after the description of turboexpanders featuring inflow radial turbines.

2. INFLOW RADIAL TURBINE TURBOEXPANDERS

The inflow radial turbine turboexpander is a turbo machine in which incoming flow enters in a radial direction and exits in an axial direction after making a 90-degree turn (Figure 1). The original expanders of the Steamboat II geothermal ORC plant were replaced by the present owner.

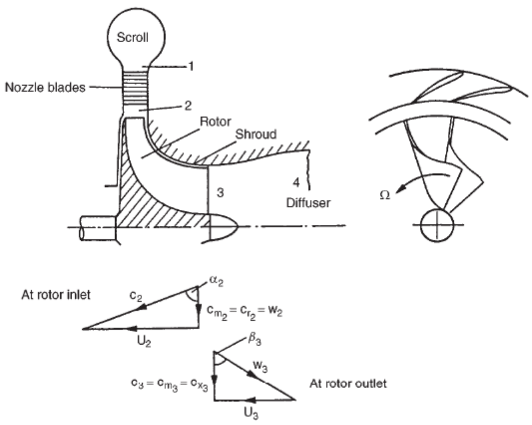


Figure 1: Radial Inflow Turbine Schematic with Velocity Triangles

A radial expander may be fit with variable Inlet Guide Vanes (IGV). In this case, process fluid flows through the IGV before entering into a radial wheel. IGV convert approximately 50% of differential pressure across a turboexpander into kinetic head and accelerate flow into the expander wheel (Figure 2).

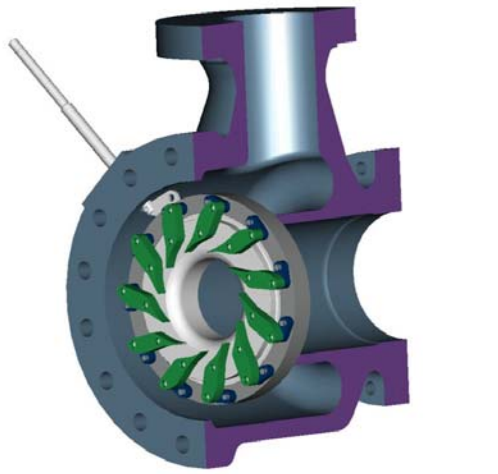


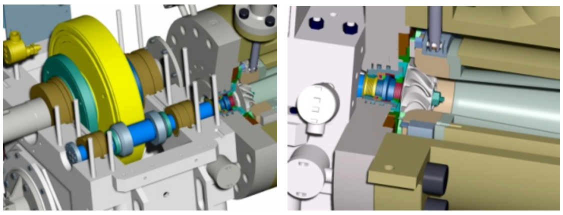
Figure 2: Radial Inflow Turbine with Variable IGariable Inlet Guide Vanes (IGV) enable the expander to control defined parameter of the process it serves. Furthermore, it directs fluid flow into the radial wheel in an optimal direction to maximize expander efficiency (Figure 3). This characteristic is particularly important for process flow conditions that are different from the initial design conditions of an expander.

Figure 3: Performance Curve of Radial Inflow Turbine with Variable IGV (Efficiency vs. Head)

An expander with variable Inlet Guide Vanes (IGV) becomes a variable geometry turbine. Later in this work, we will discuss the advantages of a variable geometry turbine in geothermal ORC plants.

The rotational speed of a turboexpander is higher than the synchronous speed of electrical generators. This poses the need for a reduction gearbox. Gearbox technology in general and integral gearbox technology in particular are mature technologies. Integral gearboxes with high gear ratio and high power have been utilized successfully in a wide range of industries and applications for many years.

A turboexpander equipped with an integral gearbox, the expander wheel is directly mounted onto the end of a high-speed pinion. This arrangement eliminates the need for high-speed coupling and hence facilitates a much simpler rotor system (Figure 4).



(a) (b)

Figure 4: Integral Gearbox

2.1 Turbine Design and Off-Design Operating Points

Turbine design requires some fundamental process data. For a geothermal ORC system turbine, the following data is usually required:

- ORC system working fluid
- Inlet pressure
- Inlet temperature
- Flow
- Discharge pressure

The output data from the design procedure for any types of turbine includes the following information and many other detailed machine design data:

- Discharge temperature
- Rotational speed
- Isentropic efficiency
- Total available power from gas stream

It is extremely important to realize that any set of design conditions defines a single point in a continuum of infinite possibilities for actual operating conditions. A turbine is in an “off-design” operation when an operating condition deviates from the original “design condition.”

A turboexpander equipped with variable Inlet Guide Vanes (IGV) is the only turbine that maintains relatively high isentropic efficiency for any off-design operating point around the design point (Figure 5).

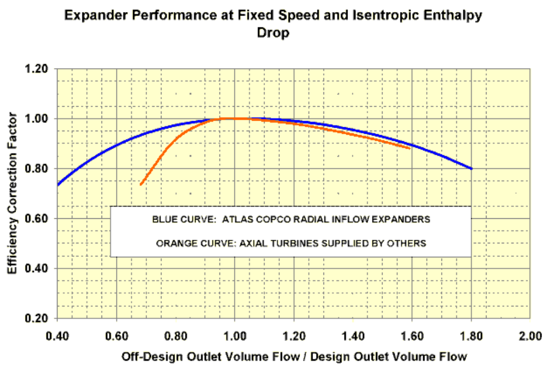


Figure 5: Performance Curve of Radial Inflow Turbines with Variable IGV (Efficiency vs. Flow)

There are numerous unknowns and probabilistic situations surrounding an ORC system operation that will cause it to deviate from its “design conditions”. A partial list of factors includes; ambient temperature, actual brine temperature, actual brine flow, NCG contents, etc.

2.2 Advantages of an Expander with Variable Inlet Guide Vanes for Geothermal ORC Systems

Figure 6 displays a simple process flow diagram (PFD) for a geothermal ORC plant. Geothermal fluid and brine flow from the production well to a separator where non-condensable gases (NCG) and steam are separated. The liquid portion flows through an evaporator to heat up and vaporize the working fluid. After leaving the evaporator, the brine is pumped back into the reinjection well.

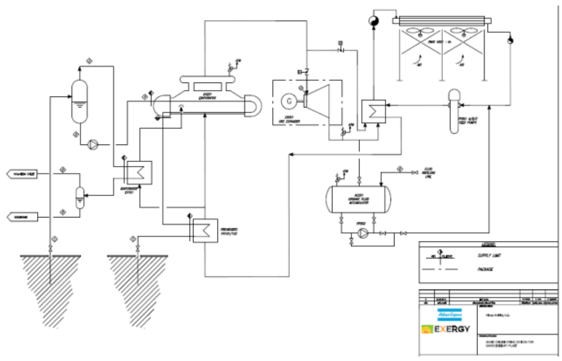


Figure 6: Process Flow Diagram of a Geothermal ORC Plant

An expander extracts energy from the working fluid vapor and cools it down. An air-cooled condenser rejects the remaining heat from working fluid vapor, to be condensed and pumped back to the evaporator to complete the cycle.

The expander operates on a differential pressure between the evaporator and condenser. The evaporator pressure should be maintained at a constant level because the heat source is relatively constant and working fluid mass flow remains unchanged. The condenser pressure, on the other hand, is a function of ambient conditions and hence variable. Condenser pressure is higher in warmer ambient temperature, during summer time, and lower in colder seasons such as winter.

Volumetric flow through the expander is a function of differential pressure across it. Controlling the expander volumetric flow is necessary to avoid chocking the expander discharge or causing other disturbances in the ORC process.

This kind of control is accomplished through a throttling valve that is installed upstream of a turbine, except in a radial inflow turbine. An expander with variable IGV does not need an external control valve. The IGV receive a signal for the desired process parameter, for instance evaporator pressure, and moves to a position that maintains the required pressure level with high precision.

This unique capability of a turboexpander – the variable geometry turbine – makes turboexpanders with IGV the most suitable choice for geothermal ORC plants in general, and those with air cooled condensers in particular. Plants equipped with expanders report availability and reliability in the 99% range (Aghai, 1977). More detailed discussions with quantitative evaluations are given by Agahi (2010).

2.3 The Largest Geothermal ORC Plants Utilizing Turboexpanders with Variable IGV

The global support of expanding the share renewable energies in the overall energy mix has increased the number of geothermal ORC projects in the world. Many projects have selected turboexpanders with variable Inlet Guide Vanes as the preferred type of turbine (Figures 7-9).

Figure 7: Enel Green America, Still Water, Nevada, USA, 4x15 MWe

Figure 8: Enel Green America, Salt Wells, Nevada, USA, 2x15 MWe

Figure 9: Celikler Jeotermal, Pamukuren I & II, Turkey, 2x25 MWe

3. CONCLUSION

Inflow radial turbine expanders with variable Inlet Guide Vanes (IGV) have a long and successful history of applications and continuous operation in the industry. Energy recovery in general and geothermal plants in particular have benefited from their high efficiency, reliability and availability for more than 30 years. Geothermal Organic Rankine Cycle (ORC) plants are considering expanders as the first choice in equipment.

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