Ejectors in a Compressible Network for Gas Turbine Extended Operability

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Summary

Gas Turbines are generally optimized to work at full load condition. To extend their operability at partial load while still keeping NOx emissions under control, some specific issues must be addressed. Turbine wheel spaces are cooled with air extracted from one of the early compression stages; under partial load the compressor bleed pressure reaches a value slightly lower than that of the turbine wheels, making the cooling ineffective and in the worst case, reverse flow must be avoided.

In order to overcome this situation, a solution involving an ejector has been implemented. The motive air, which comes from one of the last compressor stages, is used to avoid a reverse flow into the turbine wheel space through mixing with the air extracted from the early stage.

A dedicated Flowmaster network, developed to validate the solution, is capable of simulating the ejector discharge conditions to validate the solution to this phenomenon. The compressor stage pressure and temperature maps as well as the turbine wheel space conditions are provided as a function of operability parameters (IGV, ambient temperature) through 3D surfaces.

Since the ejector components for compressible networks are currently not available in Flowmaster code, a specific algorithm was implemented making use of the performance curves that correlate the suction flow with the pressure difference between the ejector exit and the suction inlet. The ejector acts like a connection between three disjoint networks, allowing Flowmaster to find a consistent path through the network branches.

Keywords

Ejector, Flowmaster, Gas Turbine, Wheel Space, Cooling, Compressible, Chocking

Introduction

Gas Turbine wheel space cooling is conventionally done through airflow extracted at the compressor 4th stage. This solution provides air at a sufficiently low temperature such that a minimal bleed can guarantee the correct cooling without sacrificing the GT efficiency. In the gas turbine cooling system this component has a double function: one is to cool the wheel space without incurring a high temperature alarm due to air extracted from one of the last stages of the compressor; the other is prevention of the reverse flow that occurs when the IGV angle is under 56° during partial load conditions.

When the GT is running under NO_x emission control at partial load, the pressure at the compressor 4th stage can be slightly lower than that of the turbine wheel space pressure, leading to a possible reversed flow that will void the wheel space cooling capability.

Such operating conditions are referred to as “extended operability” and may occur several times during the GT life cycle for specific applications.

An alternative solution to the conventional method is therefore needed and can be achieved by means of an ejector that, using air extracted from the compressor 10th stage as a motive flow, will extract air from the compressor 4th stage. The mixed air thus obtained must have sufficient pressure and flow to correctly cool the turbine wheel space.

In order to validate the feasibility of this solution, a 1D CFD analysis in the compressible steady state domain was performed. The network built in Flowmaster code models the ejector component as logic connecting three network branches (motive, suction and ejected) through the ejector performance curve received from the supplier

The ejector is mainly composed of three sections: the nozzle, the throat and the diffuser. The nozzle accelerates the suction flow through the motive flow, the throat is the section where the mixing occurs and the diffuser is the section in which the velocity energy is partially converted to pressure energy before the mixed flow exits (Fig. 1).

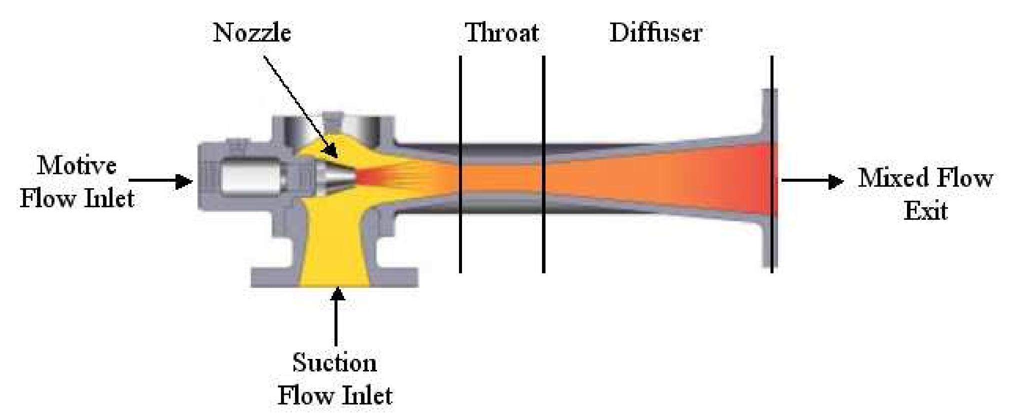

Figure 1: Ejector Schematic Diagram

Ejector Analysis

In order to investigate the suitability of the ejector for the scope described above and to identify the optimum approach, the mathematical equations governing the phenomena were analyzed.

Mathematical Approach

The assumptions used to develop the mathematical approach are listed below:

- One dimensional analysis
- The phenomena are considered to be at steady state conditions
- The compressible flows are considered real
- No heat exchange with the environment
- Friction phenomena are included

The conservation of mass, momentum equation and energy balance, as shown below, are the equations describing the ejector phenomena.

$$\begin{cases} d(\rho u) = 0 \\ dp + \rho u\, du + \frac{1}{2}\rho u^2 \left(\frac{f\, dx}{D_H}\right) = 0 \\ dh_0 = h + \frac{u^2}{2} = 0 \\ u_{motive} = a = \sqrt{\gamma R T_s} \end{cases}$$

where: ρ= density, u= fluid velocity, p= pressure, f= friction coefficient inside the pipe, h= enthalpy, D_H= hydraulic diameter of the pipe

The ejector performance is generally influenced by the geometry; in particular the throat length improves the flow mixture affecting the velocity distribution before the divergent section, whereas the diffuser shape affects the pressure recovery at the exit section.

Based on these geometric dependencies and on the fact that the motive flow nozzle conditions can undergo a choking state depending on the motive-ejected pressure ratio, the introduction of a user defined Flowmaster element into the above mentioned mathematical description is not always feasible. A more custom-like approach based on the supplier's ejector performance curve was defined.

Flowmaster Network and Simulations

A 1D CFD network including all the components present in the actual layout was built in Flowmaster code. Ejector components do not exists in Flowmaster for the compressible domain, therefore an alternative solution was implemented.

Three disjoint branches having all the necessary components (bends, reducers, pipes, etc.) are linked together through the ejector performance curves. This is a 3D graph relating the ejected mass flow rate and pressure difference between the suction and discharge with the motive pressure.

To set the GT operating conditions, the IGV angle and external temperature are used throughout the network as global variables and used as input variables to control the compressor 4th and 10th stage pressures and temperatures as well as the turbine wheel space pressure.

“General controller” elements are used to collect the IGV angle and the external temperature, and use them for the table look-up to get the compressor stage working conditions, turbine wheel space pressure and ejector performance parameters. The turbine wheel space pressure is obtained through a script defined within the controller where the velocity, mass flow rate and density are passed in via gauges.

The “wheel space behavior FR5” script uses the IGV and external temperature values to look up the equivalent loss coefficient (k) of the turbine channels and passages as well as the internal pressure (Pws) provided by the “secondary flow” department (AT-HEAT HT & Secondary Flow).

Considering the casing entrance and the turbine channels as passive items following the rule Dp=1/2*ρ*v2 and considering that the general controller can only set a total pressure (it is attached to a node, and nodes cannot be specified with static pressure), the controller pressure value will be P=Pws+Pd+Dp where Pd is the dynamic pressure associated with the flow.

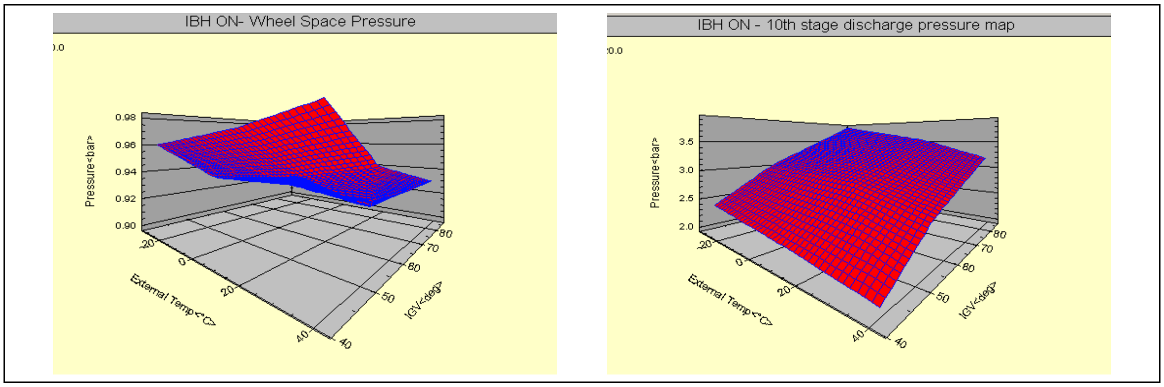

Figure 2: Wheel Space & 10^{th} stage discharge pressure Map (function of IGV and Ext Temp)

Since the ejector component is activated or deactivated depending on the 4th stage pressure value, a general controller switches off the valve component controlling the 10th stage flow whenever the static pressure monitored by the gauge exceeds the value of 1.37bar.

Whenever the 4th compressor stage pressure reaches the threshold (1.37bar), the motive flow valve switches off and the ejector begins to work as a passive item, introducing an extra resistance to the network.

The ejector supplier provided us with the flow vs. pressure drop at different inlet pressures, which was used to compute a loss coefficient assuming the cross sectional area to be equivalent to a 4” pipe (ejector suction connection). The loss coefficient is than converted to a CV vs. valve opening and is used to characterize the valve behavior.

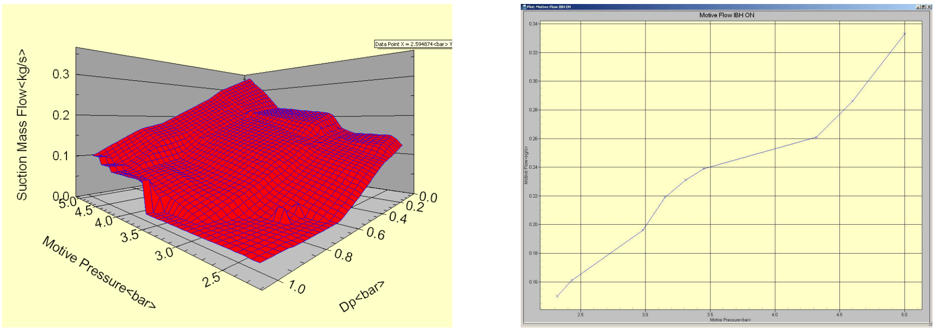

Figure 3: Wheel Space Pressure Map (IGV and ext temperature dependency)

The ejector is not represented in the network as a component; rather, its behavior is defined through the General Controller specifying the mass flow rate (positive if entering the system or negative if exiting) on each of the three branches.

Performance curves were provided at several motive pressures as the suction mass function of the pressure difference between the discharge and suction lines. The ejector performance surface map is obtained by joining all these curves in one 3D surface; due to the different nature of all curves, this surface can be considered to be a “hybrid”.

Any slice made for a given motive pressure belongs to a specific “motive pressure / suction pressure” according to the 4° and 10° stage axial compressor maps. This means that changing the compressor characteristic curves and/or running the GT with or without IBH may potentially change the ejector surface map.

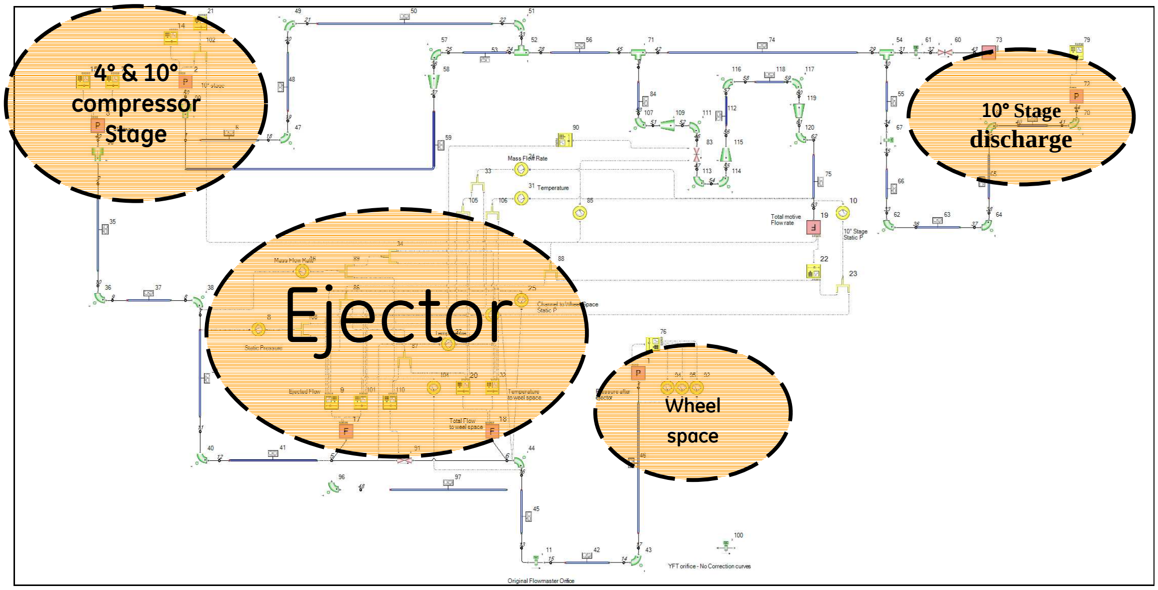

Figure 4: Ejector Network

The surface map is used to determine the flow to be extracted from the compressor 4th stage line; this will then be added to the 10th stage flow obtained from the curve above and provided to the turbine flange. The 10th stage flow is obtained through a curve that relates the motive flow to the motive pressure; since the ejector nozzle is always chocked, the flow will be linear. A local non-linearity in the region between 3 and 4 bar indicates a potential shift of the shock wave location within the ejector nozzle.

Similar to the wheel space pressure, the “secondary flow” department (AT-HEAT HT & Secondary Flow). provided the pressure map for the 10th stage discharge line (see Fig. 2).

This map is used to define the counter pressure for the turbine casing connection where the line departing from the 10th stage compressor is attached.

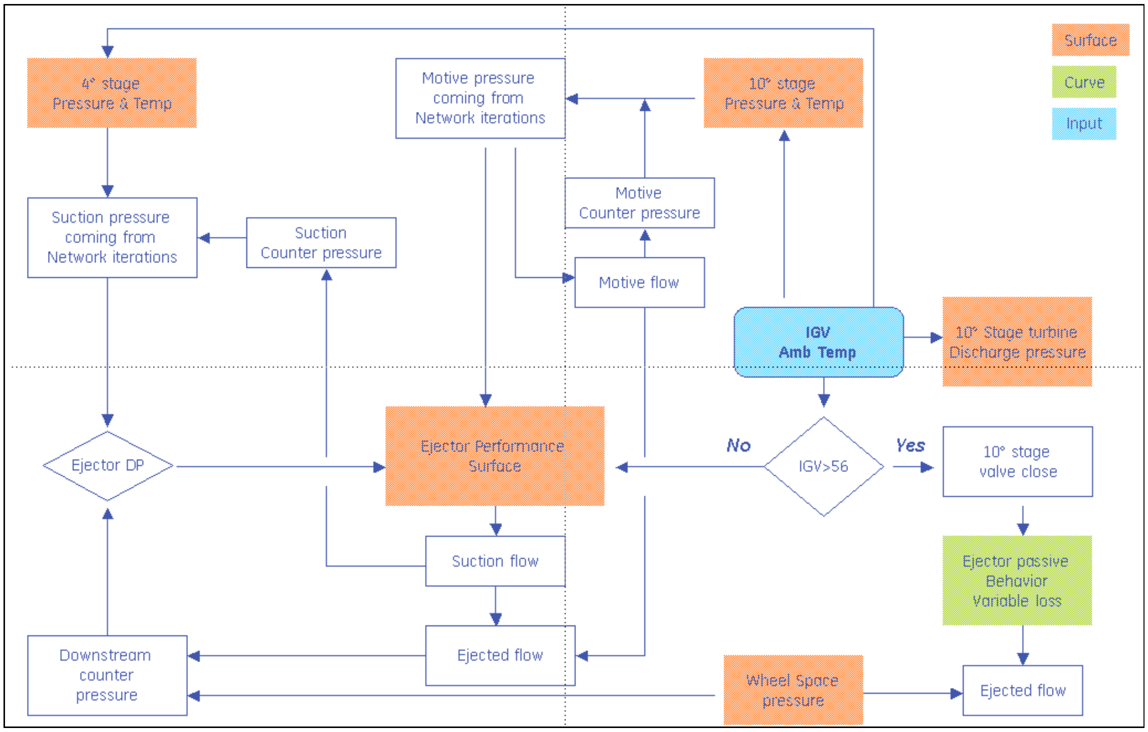

Figure 5: Ejector Network logic

Results and Discussions

The surfaces used in the network employ a linear interpolation between the data points, however, once the input values fall to the edge of the X-Y map, Flowmaster takes a stepwise constant response, failing to interpolate the result. Any script used in the network contains an algorithm to slice away the very small portion of the surface for a more appropriate interpolation.

The mass flow rate as well as the flow temperature were compared to the data measured during a GT string test, highlighting a potential mismatch of the ejector performance surface provided by the supplier compared to the actual component behavior.

This drove the team to set up a dedicated test bench to obtain more robust ejector characteristics over the entire working range. The mass flow as computed through the ejector performance test curve differs by about 10-15% from the GT string test results, whereas using the performance curves received from the supplier resulted in a difference of up to 30%.

The air temperature predicted using the supplier performance curve is roughly 10°C higher than that of the test results, whereas using the ejector performance test curve temperature matched the predicted test results.

The tested values from the upper and lower cooling lines differ substantially from each other. There appears to be a strong dependence on the ejector component.

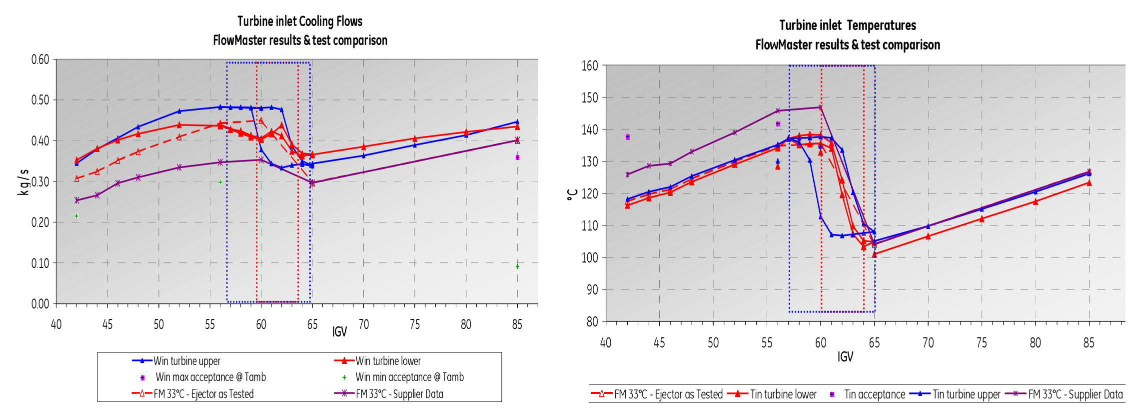

Figure 6: Ejector Performance

Conclusions

Unlike the older approach requiring extensive testing of the hardware under evaluation, the introduction of computational methodologies such as provided by Flowmaster helped the team to gain insight into all the possible dependencies through sensitivity studies and "what if" analyses.

The unexpected match of temperature and mass flow rate enabled the GE Oil & Gas Engineering team to implement a design change on the GT wheel space cooling configuration, introducing the ejector as a standard component to replace the older system layout, which inherently limited the GT operability range.

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