

Retrofit of gas turbines by SwirlFlash® over-spray

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Summary

This paper describes a new and unique technology for over-spray injection of gas turbines, called the SwirlFlash® technology. The SwirlFlash® technology uses hot pressurised water to obtain tiny droplets, which behave like aerosols. When injected in a compressor the evaporation rate is extremely high and blade impact is avoided. The basic idea is to modify the gas turbine inlet by adding a bank of SwirlFlash® spray nozzles. By injecting atomized water in the compressor of a gas turbine the parasitic work of the compressor is reduced due to quasi-isothermal compression. As a result the compressor discharge temperature is reduced. To keep the turbine inlet temperature constant, the gas turbine will demand more fuel. Due to less parasitic work and more fuel the turbine output rises significantly. In addition the combustion air is humidified and lower in temperature. This causes a lower stoichiometric adiabatic flame temperature in the combustor, resulting in lower thermal NO_x formation. Both effects are significant. The power output rises by 10-25%, the NO_x emission reduces by 25-40%. The cooler and humidified compressed air provides also better cooling conditions for the hot gas components, thus increasing lifetime and reducing maintenance costs. The SwirlFlash® systems is patented and extensively tested. It is installed in an ABB 9D gas turbine of the Amer power station in Geertruidenberg, the Netherlands.

1 Introduction

The number of standalone or combined-cycle integrated gas turbines is growing steadily. In recent years various water-spray systems have come on the market to modify the gas turbines for better performance under hot conditions. These systems range from inlet-air chilling systems by humidifiers to compressor over-spray systems. This paper deals with a unique and innovative over-spray injection system, called the SwirlFlash® technology. Normally over-spray injection systems work with the spray injection of cold water but the problem is to atomise the water to a droplet size, sufficiently small to avoid compressor blade erosion. The SwirlFlash® technology uses hot pressurised water to obtain much smaller droplets, which behave like aerosols. As a result the evaporation rate in the compressor is extremely high and blade erosion is avoided. The basic idea is to modify the gas turbine inlet by adding a bank of SwirlFlash® spray nozzles. Approximately 2% water to the mass flow results in a significant increase in the gas turbine's power output. Since moisturised combustion air will now enter the combustion chamber with a lower temperature due to the lower compressor discharge temperature, the SAFT (stoichiometric adiabatic flame temperature) will be reduced, resulting in lower thermal NO_x production. The gain in turbine efficiency and the sales of extra power offsets the loss of water and the modification costs.

2 Basic ideas

The basic idea is to reduce the work for adiabatic compression by the injection and subsequent evaporation of water in the compressor. The compression of air requires less energy at low temperatures than at high temperatures, because of the smaller volume. It is not unusual for water to be present in compressors (during cleaning, for example, or in an aircraft turbine, when flying through clouds or rainstorms). However, round-the-clock water injection could cause problems with erosion, water separation etc. The droplets must therefore be small. The computer model "FLUENT" predicts that droplets of about $2\ \mu\text{m}$ must be produced if impact damage on the metal surfaces and the separation of liquid water are to be avoided. Experiments show that this can be realised by the so-called SwirlFlash[®] technology. The water to be sprayed is pressurised and heated up. Then, as it spouts out-of a swirl nozzle, explosive flashing takes place. The result is a surprisingly fine hot plume of tiny water droplets, ready to evaporate as they enter the compressor. By using a swirl nozzle and by supplying pressurised hot water, the combination of spraying and flashing results in droplets roughly ten times smaller in diameter and thousand times smaller in volume and weight than the droplets of a normal swirl spray device. In the SwirlFlash[®] mode a 0.4 mm nozzle produces about two-trillion droplets per second!

The amount of heat extracted from the compressor air by evaporation is much greater than the amount added through the hot water spray. As a result, the temperature drops and the compressor discharge temperature is reduced. This results in less parasitic work of the compressor and a higher output and efficiency of the gas turbine. Finally the NO_x emission is reduced due to the lower flame temperature and the hot components are cooled better, resulting in life extension. These aspects will now be discussed.

3 Retrofit features

A number of issues must be considered when over-spray injection is taken into account:

- 3.1 the evaporation rate in the compressor
- 3.2 the compressor behavior
- 3.3 the ambient conditions of temperature and humidity
- 3.4 the lifetime of the hot components
- 3.5 the flame stability and NO_x emission
- 3.6 operational aspects like flexibility

3.1 The evaporation rate in the compressor

The residence time of air in an axial compressor is, depending on its size, about 10 milliseconds. It's not that easy to evaporate a significant amount of water in a couple of milliseconds given the amount of heat, available in the compressor. The effect of water evaporation has been calculated in a 1-D compressor model of a GE Frame 6 and all aspects of the compressor (such as velocity triangles, temperature rise, pressure build-up, compressor efficiency, water content, shift in working point etc) have been assessed. It was shown that tiny hot droplets of 2 μm evaporate in the first three stages of the compressor (see Figure 1). The amount of compressed air, efficiency reduction and compressor discharge temperature are all in compliance with measurements, done during a test at a small 400 kWe gas turbine.

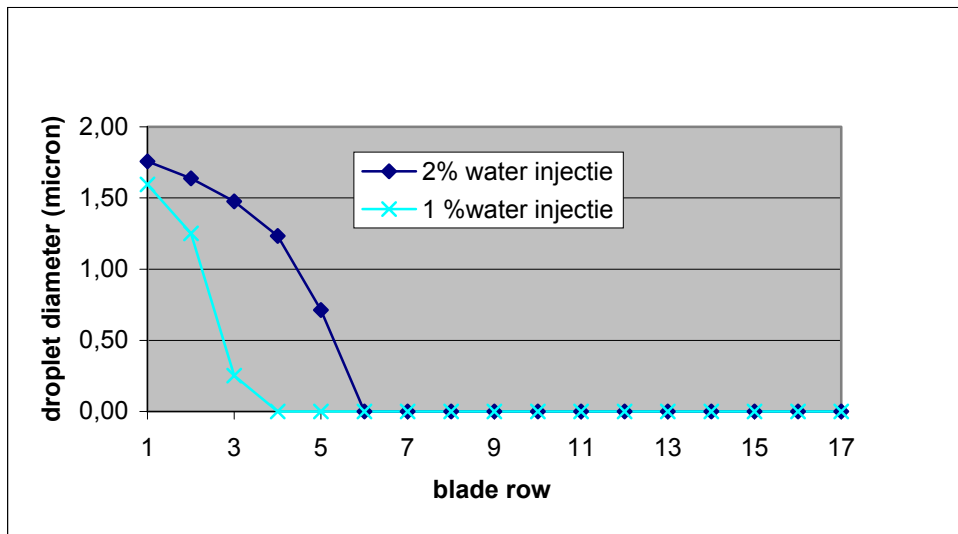


Figure 1: droplet evaporation in a GE Frame 6 turbine for 0%, 1% and 2% over-spray injection.

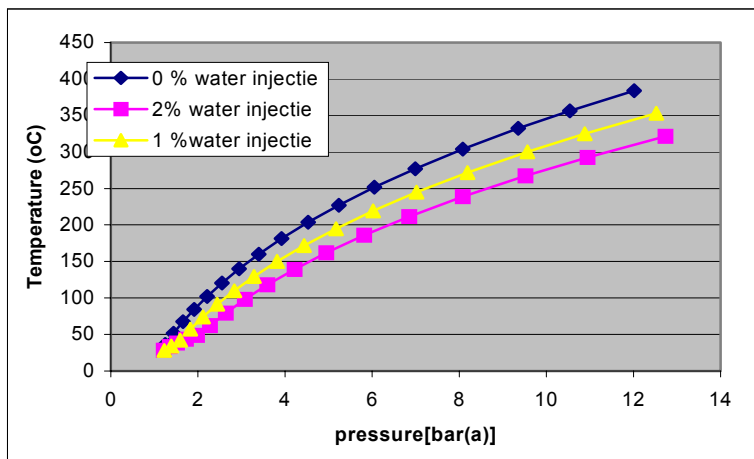


Figure 2: temperature rise in a GE Frame 6 turbine for 0%, 1% and 2% over-spray injection.

3.2 The compressor behavior

Gas turbine compressors are designed for a one-phase flow of air. Adding water droplets results in a two-phase flow and subsequently a shift, away from the optimum working point. The possibility of surge and/or stall must therefore be examined to make sure that no problems are to be expected. In addition vibration of the blades, a change in tip clearance and blade erosion could be anticipated when the retrofit is not properly carried-out. So far experiments with the SwirlFlash[®] over-spray systems showed none of these problems, provided that the amount of water is limited to 2% on mass basis and the droplets have the required size of 2-3 μm . Detailed CFD-analysis show that certain locations in the compressor can sometimes even show a slightly favorable behavior.

3.3 the ambient conditions of temperature and humidity

The SwirlFlash[®] technology has a very favorable behavior when it comes to applicability under various ambient conditions. The classical inlet air chillers can only work properly at high temperatures and low relative humidity. The cold water over-spray injection systems are limited to ambient temperatures above 10 °C in order to avoid ice formation at high air velocities. The SwirlFlash[®] system, however, can be used in a much wider range. At high temperatures and high humidity the evaporation takes almost completely place in the compressor. At high temperatures and low humidity the systems realizes inlet air chilling while the remainder of the water evaporates in the compressor. At low temperatures (0 °C) and high humidity the hot spray acts as an inlet air de-icing system and can still be used. Only when the humidity of the inlet air is close to zero, the inlet air temperature must be 5 °C in order to avoid ice formation. These features result in a far wider range of temperatures and humidity, where the SwirlFlash[®] over-spray can be applied. As a result of that, the amount of extra generated MWh's is far greater than any other system. The effect of over-spray injection of various quantities of water at different temperatures is shown in Figure 3.

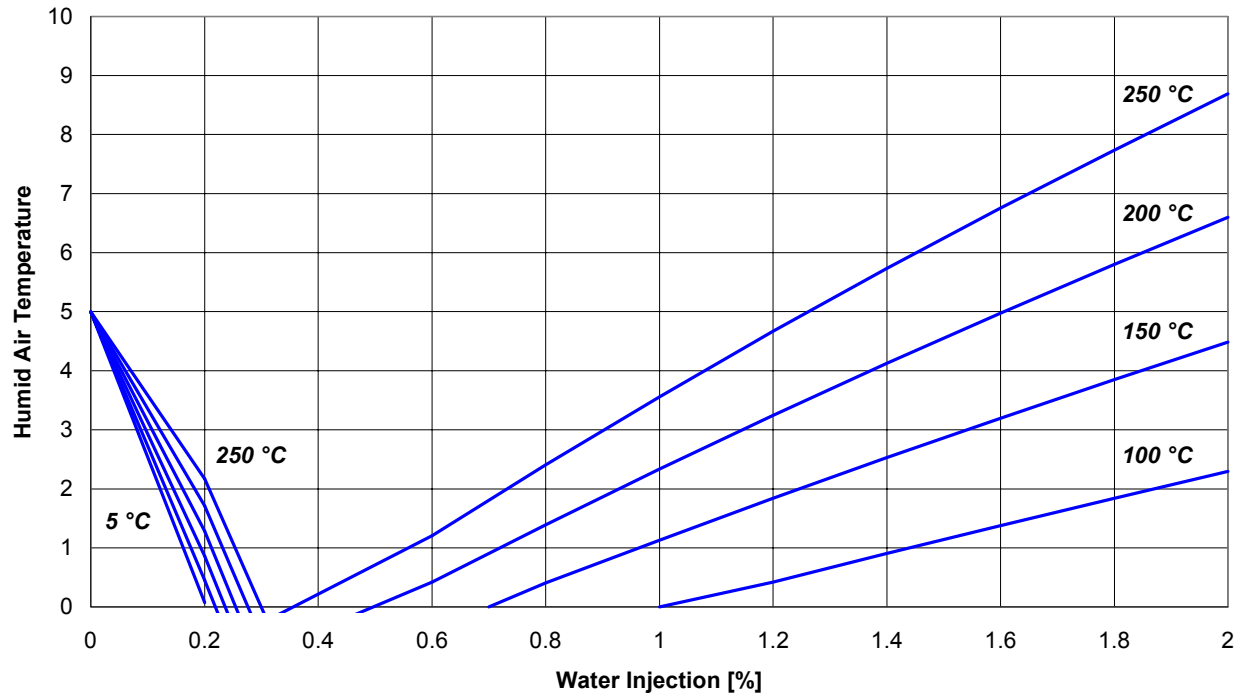


Figure 3: effect of over-spray injection of various quantities of water with different temperatures (5 °C, 50 °C, 100 °C, 150 °C, 200 °C and 250 °C) on the inlet air temperature. Vertical axis: air temperature after injection. Horizontal axis: amount of injection water. Inlet air conditions: 5 °C, 0% relative humidity.

3.4 The life time of hot components

The maintenance costs of the gas turbine are reduced due to lower temperatures of the hot gas parts. The reason for this is that the available cooling air is about 50-60 degrees colder than the normal cooling air, while approximately 1% more air is available. In addition the air contains more water vapor, as a result of which the heat transfer properties increase and the cooling effect is more pronounced. This results in an extended life of the hot gas components. This effect has been calculated for the first row of rotor blades in a frame 6 turbine, using the REMLIF program for life assessment of turbine blades. The average material temperature of the blades drops by about 7 K. This is significant when it comes to creep as a failure mechanism. It results in life extension from 32.000 hrs to 44.000 hrs, an increase of about 40%. A similar calculation for the hot liner in the combustion chamber of a Frame 9A turbine revealed a 6 K lower liner temperature which is favorable from the point of view of oxidation and creep. Should the turbine be operated in a cyclic mode, than the results are not necessarily applicable. The temperature gradient over the wall of the blade or the liner becomes slightly steeper. During frequent cycling of the turbine this might cause a mixed failure mechanism of creep and low-cycle fatigue. These operational conditions should be examined in more detail.

3.5 Flame stability and NO_x emission.

The NO_x emission permits are under pressure by governmental regulations. Today a large number of gas turbines are equipped with steam or water injection. This reduces the NO_x emission significantly. But steam injection is expensive (about 2800 Euro per ton) since the steam must be produced from fuel, which would otherwise be available to produce power. Water injection is cheaper, but results in a decreased turbine efficiency and quite often in expensive repairs while the cold spray causes cracking of the hot components. By modifying the water injection and shifting it to the compressor inlet, a similar NO_x reduction can be achieved but at much lower costs (1680 Euro per ton). In both situations the water is lost, but in the latter case the injected water augments the power output and at the same time reduces the NO_x production. When the power can be sold, the costs for NO_x reduction can significantly be reduced. It appears from tests that the flame stability is not affected by introducing humidified air in the combustor, not even for a dry low-NO_x combustor. The NO_x-reduction for a conventional diffusion burner can be as high as 40%, for a dry low-NO_x burner it is typically 25%.

3.6 Operational aspects like flexibility

Flexibility becomes an increasingly important asset for power generators. The introduction of power exchanges and the observed price volatility in a liberalized electricity market increase the need for flexibility of the power plants. The over-spray injection creates an extra degree of freedom in the operation of the facility. The power increase of about 10% is almost instantaneous. This gives the operator new ways of handling power demand from its marketing and sales department.

4 Example of a gas turbine retrofit

As an example, the impact of water injection in an ABB 9D gas turbine is calculated. In table 1 the results are summarised for dry operation and for the injection of 1%, and 2% of hot water (250 °C) directly in front of the compressor. The ambient conditions are according ISO (15 °C, 101.325 kPa, 60%)

Table 1 Calculation of an ABB 9D gas turbine retrofit with the SwirFlash[®] technology.

Air intake	Water injection	Compressor discharge T	Fuel supply	Output	Efficiency LHV
(kg/s)	(kg/s)	(°C)	(kg/s)	(MWe)	(%)
148.7	-	297	3.0	29.5	25.8
148.6	1.5	272	3.2	31.9	26.5
146.9	2.9	245	3.3	33.6	26.9

It can be observed that for 2% injection the compressor discharge temperature is reduced by 52 K and that the total mass flow through the compressor increases slightly from 148.7 kg/s to 149.8 kg/s. The power output rises by 14% when the polytropic efficiency of the compressor is unaffected. In practice the output will increase by about 10% due to a lower compressor efficiency. The total efficiency of the gas turbine increases by 1.1 %-point.

This ABB GT 9D gas turbine is part of the specific arrangement of the coal fired power plant Amer 8 (645 MWe) and is the first turbine to be equipped with the SwirFlash[®] technology. The objective is to reduce the NO_x emission of 247 g/GJ by 40% to 150 g/GJ. In this particular case the hot water is taken from the high-pressure pre-heaters in an arrangement, as shown in Figure 4. Since the water is heated-up by the preheaters in the steam turbine cycle, the output of the steam turbine will be reduced. On the other hand the energy content of the flue gas has increased. This results from the lower compressor discharge temperature of the gas turbine and the subsequent extra fuel injection to keep the turbine inlet temperature constant. The larger amount of flue gas will not only increase the output of the GT expander. In addition the isobaric specific heat–C_p and the temperature of the flue gas will increase, thus providing extra energy to generate additional steam for the steam system. This extra energy compensates for the extraction of hot water from the pre-heaters and the subsequent reduction in power output of the steam turbine. This configuration results in a slight overall efficiency decrease, but the output increases significantly and the customers request for NO_x reduction is met.

Table 2 Effect of water injection and evaporation cooling in the compressor of an ABB GT9D in a "combined cycle" mode with the steam system of a pulverised coal fired boiler.

	air (kg/s)	water (kg/s)	flue gas (kg/sc)	flue gas MW	Output (MW)	η_{cc} (%) (LHV)	SAFT (°C)
GT 9DCC 0% water	148.7	--	151.7	83.0	29.5	39.54	2192
GT9DCC 1% water	148.6	1.5	152.8	84.5	32.0	39.54	2152
GT 9DCC 2% water	146.9	2.9	152.2	85.4	33.5	39.53	2107

The increase in output and the lower SAFT (resulting in lower NO_x) is interesting enough to consider this type of modification. The investment costs for this modification are less than for a stand-alone gas turbine since the hot water supply and a demineralization installation are available. The choice of how to integrate the SwirlFlash® system in the existing power plant is indicated in Figure 4.

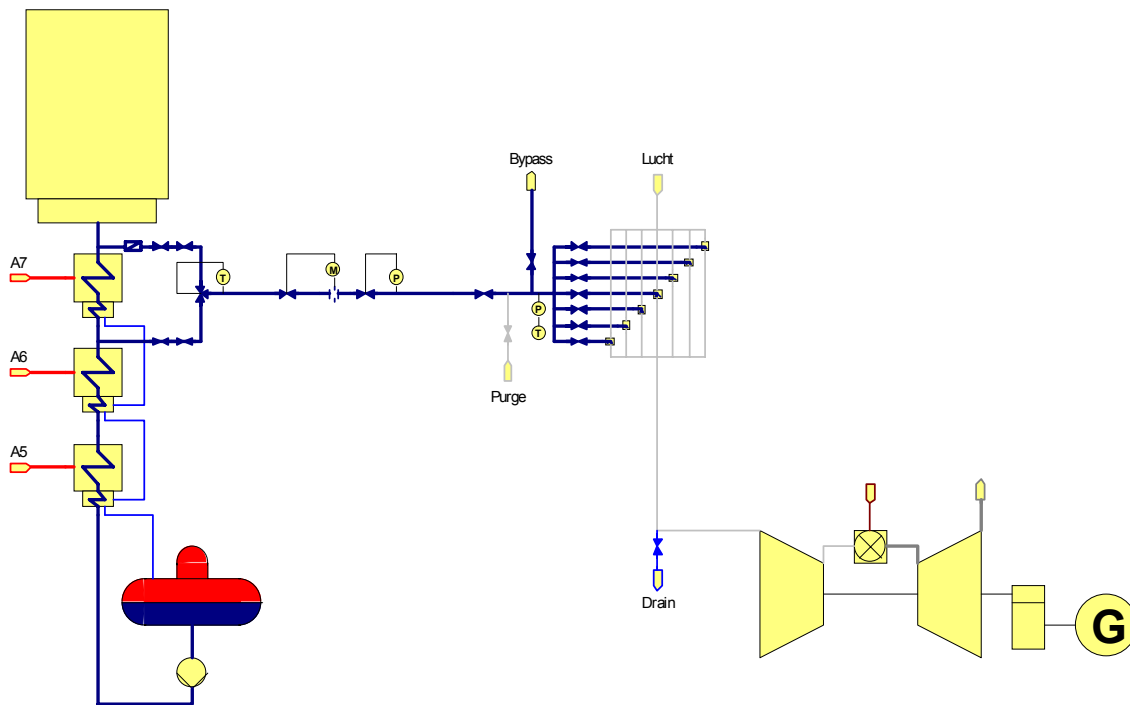


Figure 4: retrofit of a ABB-GT9D operating in an arrangement with the coal fired power station Amer 8, utilizing the heat and water supply of the steam cycle.

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