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COMPARISON OF BLADE COOLING PERFORMANCE USING ALTERNATIVE FLUIDS

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ABSTRACT

CO_2 emissions reduction has become an important topic, especially after Kyoto protocol. There are several ways to reduce the overall amount of CO_2 discharged into the atmosphere, for example using alternative fluids such as steam or CO_2. It is therefore interesting to analyze the consequences of their usage on overall performances of gas turbine and blade cooling systems.

The presence of steam can be associated with combined or STIG cycle, whereas pure carbon dioxide or air-carbon dioxide mixtures are present in innovative cycles, where the exhaust gas is recirculated partially or even totally.

In this paper we will analyze a commercial gas turbine, comparing different fluids used as working and cooling fluids. The different nature of the fluids involved determines different external heat transfer coefficients (external blade surface), different internal heat transfer coefficients (cooling cavities) and affects film cooling effectiveness, resulting in a change of the blade temperature distribution.

Results show that the presence of steam and CO_2 could determine a non negligible effect on blade temperature. This means that cooling systems need a deep investigation. A redesign of the cooling system could be required. In particular, results show that steam is well suited for internal cooling, whereas CO_2 is better used in film cooling systems.

Keywords: carbon dioxide, steam, blade cooling.

INTRODUCTION

In last years, the improvement of energy conversion efficiency and the reduction of pollution have become of primary importance in energy system evaluation. The purpose of Kyoto protocol is to push governments energetic strategies towards a more friendly environmental policy. This means that some gas emissions, particularly carbon dioxide, must be reduced or drastically cut down. Two possible solutions are available in order to reduce carbon dioxide emissions. The first one is rising the energy conversion efficiency. There are several ways to increase efficiency, for examples using combined cycle instead of simple Joule-Brayton cycle and/or modifying the turbine operative conditions, such as pressures and maximum temperature. The second solution is the development of innovative thermodynamic cycles with carbon dioxide as working fluid. Considering the latter, an analysis of the effects, on gas turbine hot parts, of carbon dioxide as working fluid is very important.

To reduce the amount of CO_2 directly discharged into the atmosphere, several innovative cycles can be considered [1]. In these cycles the concentration of carbon dioxide is raised, thus the fluid can be eliminated by absorption or by storing facilities. In this work we focus the attention on gas turbine cooling systems design considering the presence of facilities for CO_2 emissions reduction. First stage nozzle and blades are always a critical part of a gas turbine, thus it is of primary importance the assessment of cooling performances using alternative fluids.

Air from compressor is the most widely used coolant and a lot of research studies on air cooled blade have been performed. Nevertheless, because of its poor cooling properties, a lot of air is usually needed causing high thermodynamics losses.

In last years some alternative fluids were investigated, especially for heavy duty applications. In particular, steam cooling suits to combined cycle, e.g. MS7001H by General Electric [2, 3] and 501ATS by Siemens-Whestinghouse [4]. Steam as coolant is only convenient when it is already available in the plant, such as in STIG cycle or Combined Cycle [5]. In an Open Cooling Loop system (OCL) the steam is discharged at the end of the cooling path and expands in the gas turbine. This is applicable in STIG plants, in which the steam is already injected before turbine inlet. Closed (CCL) or Semi-closed Cooling Loops (SCL) are more useful in combined cycle plants: the cooling steam is recovered by some return ducts and then it expands in the bottomer cycle. An example of this method is the H System of General Electric [2, 3] in which steam is used with CCL method in the first two stages. Thus, the cooling system becomes the bottomer overheater. Another example is the Siemens Westinghouse 501ATS gas turbine [4], in which high pressure steam, used in closed circuit, cools the first and second nozzles, whereas the rotor blades are cooled, always in closed loop, by air. Other researchers studied cooling system improvements using steam cooling and mixed steam/air cooling [6].

CO_2 as coolant can be used in innovative cycles, in which pure CO_2 or CO_2 enriched mixtures are also used as working fluids [7]. These innovative cycles are being developed in order to reduce CO_2 emissions because high CO_2 concentration helps the absorption and/or storage of this gas. Several concepts for collecting CO_2 from gas turbine power plants were studied. One of these uses closed or semi-closed thermodynamic cycle, in which the working fluid is entirely CO_2, obtained by totally exhaust recirculation [7-10]. CO_2 can then be collected directly into storing facilities. There are also semi-closed cycles [8, 9] where only a fraction of the exhaust gas is recirculated. In this case it is necessary to introduce a chemical removal equipment in the exhaust flow [11-14]. The exhaust recirculation increases CO_2 concentration: this raises the efficiency of the removal device. Blade cooling influences, using air, CO_2 and CO_2 rich mixture, on cycle performance of semi closed gas turbine configurations were investigated [15].

The purpose of this work is to analyze the influence of the introduction of these innovative thermodynamic cycles on blade cooling systems. The main goal is the direct comparison among air, steam, CO_2 and Air+CO_2 enriched mixtures (Exhaust+CO_2), used as coolants and working fluids. Boundary conditions (such as maximum cycle temperature, expansion ratio and coolant mass flow), the blade and the cooling systems geometry were fixed. In this paper we present the results of an analysis applied to an actual first stage nozzle [16].

The analysis is divided into three different steps. First, we evaluate the composition of both working and cooling fluids, carrying on a thermodynamic analysis of the cycles. In the second step, we study the expansion of working fluids by means of a two-dimensional CFD approach. Last, we determine the overall heat transfer and the blade temperature distribution.

NOMENCLATURE

ASU	Air Separation Unit	
CCL	Closed Cooling Loop system	
ESMS	Energy System Modular Simulator	
H	convective heat transfer coefficient	[W/m^2K]
LE	Leading edge (front cavity)	
TE	Trailing edge (rear cavity)	
OCL	Open Cooling Loop system	
P	power	[W]
S	abscissa	[m]
S_{max}	airfoil pressure/suction side length	[m]
SBC	Stator Blade Cooling	
SCL	Semi-closed Cooling system	
STIG	Steam injection Gas Turbine	
T	temperature	[K]

Greek symbols

β	pressure ratio
ω	angular velocity [RPM]
η	film cooling effectiveness
ε	coolant efficiency

Subscript

adbw	adiabatic wall
blade	blade metal
cool	inlet coolant conditions
hot	hot gas
exit	gas turbine exit
max	maximum value
reference	reference case (design)
wall	blade external surface
0	hot gas inlet
2	coolant exit

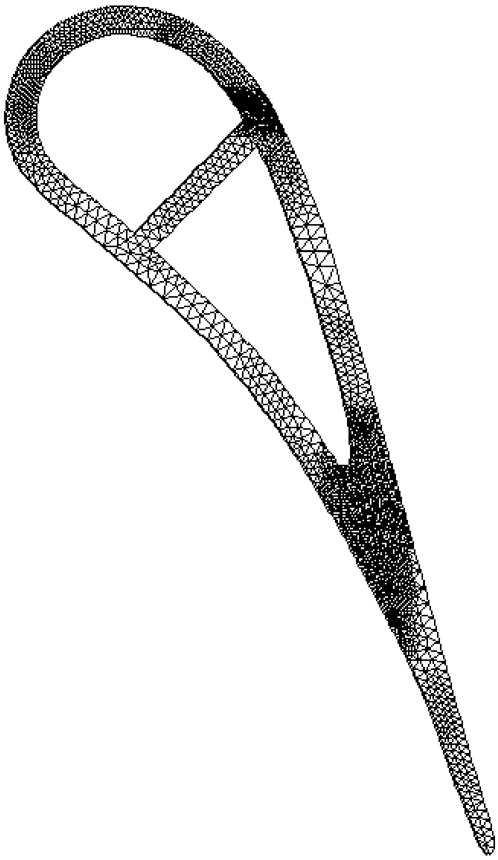

Figure 1. Conductive analysis: unstructured mesh.

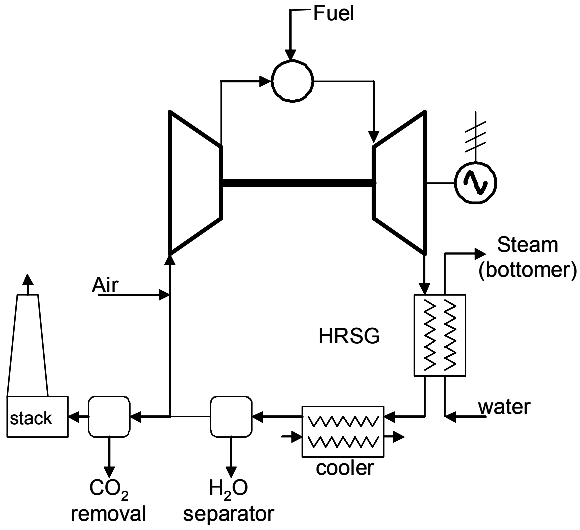

Figure 2. Semi closed cycle: CO_2 partially recirculated.

Table 1. Expected performances (ISO).

β	ω	P [kWe]	Heat Rate [kJ/kWh]	Exhaust Flow [kg/s]	T_{exit} [K]
12.5	22500	2000	14400	10.7	798

SIMULATIONS

In order to better compare fluids characteristics, we use same conditions for all simulations: our goal is a direct comparison of blade thermal loads for each case. Coolant inlet pressure and temperature and turbine inlet conditions are fixed for each fluid and for each cycle. Coolant mass flow is kept fixed.

The thermodynamic properties of each fluid were calculated through the correlations proposed by Lucas and Mason-Saxena [17].

We chose these simulations according to gas turbine cycle we decided to analyze. Moreover we studied an existent gas turbine, keeping thus unchanged overall blade and cooling system geometry. The chosen reference gas turbine is a 2MW single shaft machine suited for cogeneration in industrial applications because of its high exhaust temperature. It has a single tubular combustion chamber (silo type) and can operate with a wide variety of liquid and gaseous fuels.

The expected performances at ISO conditions are presented in table 1.

The nozzle cooling system is based both on impingement and film cooling. The blade [16] is divided into two separated cavities (Fig. 1). Each cavity is cooled internally by impingement. The coolant is then discharged through two rows of holes and provides a film cooling. The first row discharges the first cavity coolant on the suction side. The second row discharges the second cavity coolant on pressure side near the trailing edge. All the coolant is used for film cooling. The coolant mass flow rate in each cavity is kept constant in all simulations.

THERMODYNAMIC ANALYSIS

In this paper we consider four different thermodynamic cycles with four different working fluids.

The first cycle is the well known Brayton-Joule open cycle and the working fluid is burned air. This cycle is used as reference case.

The second uses pure CO_2 as working fluid. This simulation was developed to highlight CO_2 influence on external convective heat transfer. The third one is a semi-closed partially recirculated Joule cycle (Fig. 2). In such a cycle the exhaust gas is enriched with carbon dioxide (exhaust gas+CO_2). The exhaust recirculation amount is driven by the combustor: an elevated recirculation implies low oxygen level in the combustor hindering its correct working. It's notable the

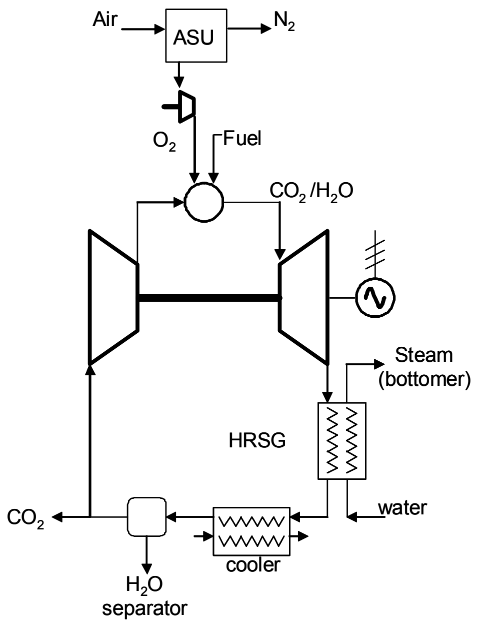

Figure 3. Semi closed cycle: CO2 totally recirculated.

presence of some oxygen in the exhaust gas, due to the cooling air bleed from the compressor.

The last one is a semi-closed totally recirculated Joule cycle (Fig. 3). The exhaust gas is almost completely recirculated, thus both the oxidizer and the fuel are injected in the combustion chamber. Usually, oxidizer is 95% pure oxygen, obtained with an ASU (Air Separation Unit) device [8]. This method gives the possibility of recovering both water and CO_2. The resulting working fluid is almost completely CO_2 and steam. No oxygen is presents in the working fluid as we suppose to use a stoichiometric concentration in the combustion chamber.

The main difference between last two cycles is the amount of exhaust gas being recirculated, respectively about 40% and 90÷95%. Of course in the first configuration the ASU device is no necessary, because the compressor air itself may complete the combustion reaction.

Analyzed cooling fluids were: air, steam, CO_2 and air enriched with CO_2 (Air+CO_2). Table 2 shows the combinations between coolants and working fluids.

Combustion and turbine expansion simulations were performed by the ESMS modular code [18]. Thus we determined gas composition, thermodynamic conditions at nozzle inlet and coolant composition.

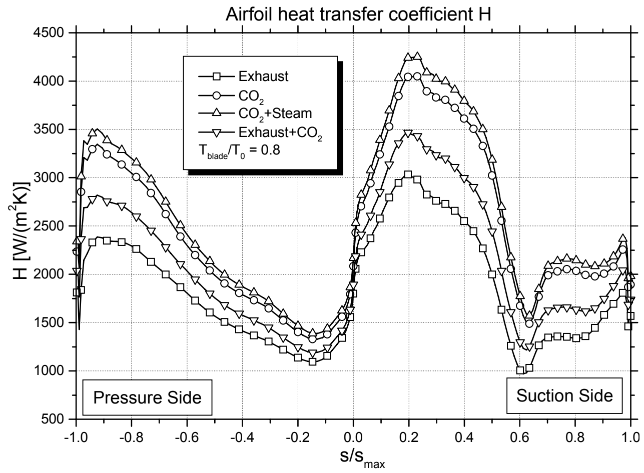

Figure 4. Convective heat transfer coefficient

Table 2. Coolant and working fluid analyzed combinations.

	Working fluid			
Coolant	Exhaust gas	CO_2 + steam	CO_2	Exhaust gas+CO_2
Air	yes	yes	yes	yes
CO_2	yes	yes	yes	yes
Air+CO_2	no	no	no	yes
Steam	yes	yes	yes	yes

An overview of computed composition of several fluids is reported in table 3.

Table 3. Fluids composition at turbine inlet.

	Exhaust gas+CO_2	CO_2+ steam	CO_2
O_2 [kg/kg_{tot}]	0.00571	-	-
N_2 [kg/kg_{tot}]	0.78129	-	-
H_2O [kg/kg_{tot}]	0.05375	0.04855	
CO_2 [kg/kg_{tot}]	0.15920	0.95145	1.0

FLUID DYNAMIC ANALYSIS

The vane flow field is computed with a two dimensional Navier-Stokes solver. We use the TRAF2D [19, 20] code to calculate pressure and velocity distribution around the airfoil. In this analysis we also evaluated the external convective heat transfer coefficients. This analysis is performed for several blade temperatures. Figure 4 shows the heat transfer coefficients for one blade temperature. It is possible to note that external thermal loads are always higher than design one. In Fig. 4 we see that CO_2 determines about 40% increment of the external heat transfer coefficient, compared to the exhaust one. A CO_2 concentration of 16% in mass (Exhaust+CO_2) causes a 15% increment of the heat transfer coefficient. Moreover, in the

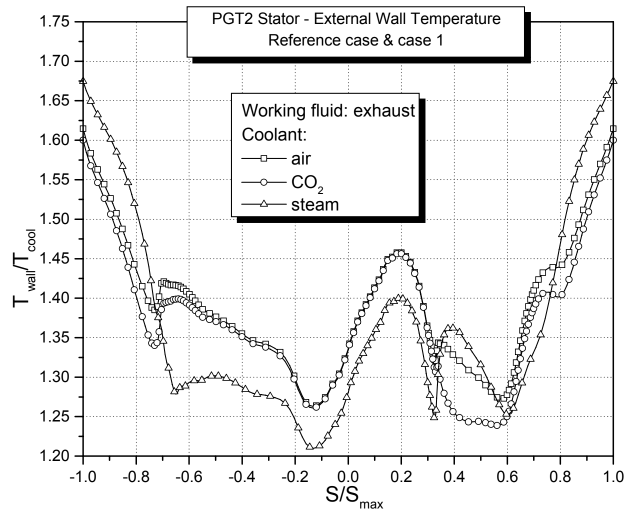

Figure 5. External wall temperature. Case 1.

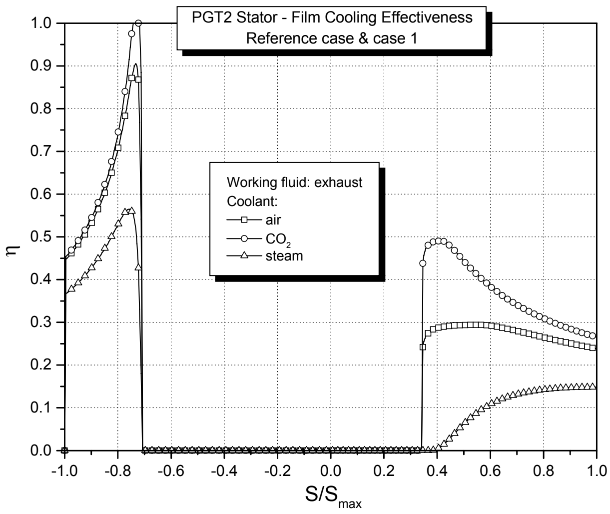

Figure 6. Film cooling effectiveness. Case 1.

CO_2+steam case (table 3), the heat transfer coefficient is also incremented by steam.

The coolant flow and the internal heat transfer are evaluated by a one-dimensional code. The cooling system is simulated with a fluid network. The coolant flow in every branch of the network was calculated by the SBC code [21], developed by "Dipartimento di Energetica" of Florence University. This code uses experimental correlations to evaluate heat transfer and friction factors. These correlations have an uncertainty of no more than 20%.

Cooling performances are usually compared using several parameters. Coolant efficiency is defined as Eq. (1):

$$\varepsilon = \frac{T_2 - T_{cool}}{T_{blade} - T_{cool}} \quad (1)$$

This parameter shows how much the coolant is "used". Another parameter is cooling effectiveness Eq. (2):

$$\phi = \frac{T_{hot} - T_{blade}}{T_{hot} - T_2} \quad (2)$$

It shows how much the blade is cooled. In other terms, effectiveness defines a dimensionless blade temperature. The last parameter is film cooling effectiveness, Eq. (3):

$$\eta = \frac{T_{adbw} - T_{hot}}{T_2 - T_{hot}} \quad (3)$$

This parameter shows how much the film protects and isolates the blade surface from hot gas. If η=0 no film exists and adiabatic wall temperature coincides practically with hot gas temperature. Otherwise, if η=1, the adiabatic wall temperature is equal to coolant temperature at injection point, and the blade protection is maximized.

CONDUCTIVE AND CONJUGATED ANALYSIS

The commercial code ANSYS® [22] was used to compute the conductive heat transfer and the blade temperature distribution, performing a two-dimensional analysis. The blade to blade section analyzed is near the mean one, where the hot gas reveals the maximum temperature. Figure 1 shows the finite element unstructured mesh. Note the mesh refinement in the film cooling injection ducts area. Finite element conductive analysis on two-dimensional blade section and isotropic material has a negligible uncertainty even with a coarser mesh.

Of course, the heat tranfer problem is conjugated, that is the convective and the conductive aspects must be resolved at the same time to obtain the overall heat transfer and temperature distribution. An iterative procedure is run until blade temperatures converge [21]. First, an arbitrary temperature is set and both external and internal convective heat transfer are evaluated (fluid dynamic analysis). These values determine a new temperature distribution (conductive analysis) and the iterative cycle starts again.

CASE 1: EXHAUST VS. AIR, CO_2 OR STEAM

This case refers to the standard Joule-Brayton open cycle used as reference cycle. In this test case there is a standard exhaust gas as working fluid while air, CO_2 and steam are coolants. The reference coolant is air provided by the compressor. Table 4 reports some results in percentage of the reference coolant (bold).

Figure 5 shows the blade external temperature profile. Negative values of the dimensionless abscissa correspond to the pressure side, positive values to the suction side. The leading edge has zero abscissa. Starting from the leading edge (S/S_{max}=0.0) and going toward the suction side, we notice temperature increase with external thermal loads (Fig. 4). Subsequently it decreases not only for the presence of impingment but also for the film cooling injected at about S/S_{max}=0.35. Finally it raises again because of the ducts lower efficiency in the trailing edge. On pressure side the external temperature profile increases according to the external heat transfer. The injection of coolant (at about S/S_{max}=0.7) slightly

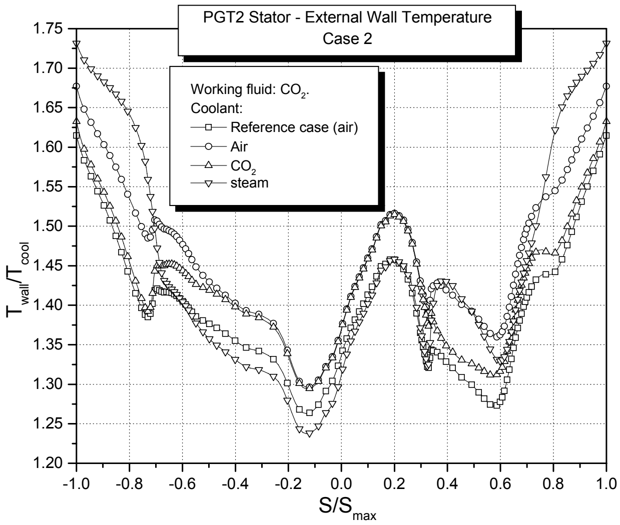

Figure 7. External wall temperature. Case 2.

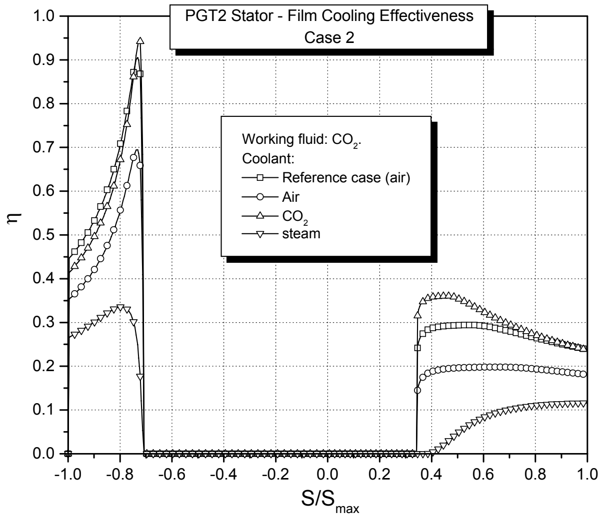

Figure 8. Film cooling effectiveness. Case2.

decreases blade temperature but in the trailing edge temperature raises again, missing the internal cooling.

Table 4. Reference & case 1 results.

	Front Cavity			Rear Cavity		
	air	CO_2	Steam	**air**	CO_2	Steam
T_2/T_{cool}	**1.0566**	-.250%	-2.26%	**1.0750**	-1.00%	-2.20%

	air	CO_2	Steam
T_{blade}/T_{cool} average	**1.3942**	-1.42%	-1.15%
T_{blade}/T_{cool} max	**1.6147**	-0.091%	+3.71%
T_{blade}/T_{cool} min	**1.2628**	-1.91%	-4.19%
LE ε	**0.1432**	+0.49%	-39.73%
TE ε	**0.1898**	-9.91%	-28.87%
Average ε	**0.1582**	-3.54%	-35.50%
ϕ	**0.5540**	+4.03%	+3.28%

Film cooling effectiveness η (Fig. 6) on pressure side is very high, but it lowers down quickly. The high value is due to the injection angle (almost tangent to blade profile) but a rapid mixing with hot gases lowers its value. On the contrary, on suction side the higher injection angle determines lower maximum values, while the effectiveness is more constant.

The CO_2 cooling system seems a little better than air one, especially in realizing film cooling. This suggests to use CO_2 in open loop cooling system with wide use of film cooling. The steam cooling system is even better in the impingement cooled zone, but it is worse in the film cooling zone (Fig. 6), determining high maximum temperature (table 4) and increasing thermal gradients towards the trailing edge. So the steam cooling seems optimal for closed loop system, without film cooling.

CASE 2: CO_2 VS. AIR, CO_2 OR STEAM

In this case the working fluid is CO_2, whereas the coolants are air, CO_2 or steam. In table 5 the test case results are presented. The coolant mass flow is the same as the reference case.

Table 5 and Fig. 7 show clearly a blade temperatures increment and generally a lessening of the cooling system performances. There are two reasons: CO_2 as working fluid presents higher external thermal loads (Fig. 4), and film cooling is weakened by the density of CO_2 as working fluid (Fig. 8). The film cooling depends on density of working fluid and coolant, in particular on their ratio. CO_2 has a lower gas constant compared to steam and air because of its greater molecular weight, thus at about the same pressure and temperature carbon dioxide has a greater density. This can explain why CO_2 as working fluid weakens film cooling, whereas CO_2 as film coolant strengthens film effectiveness.

Table 5. Case 2 results.

	Front cavity			Rear cavity		
	Air	CO_2	Steam	Air	CO_2	Steam
T_2/T_{cool}	+.69%	+.42%	-1.79%	+1.62%	+.46%	-1.26%

	Air	CO_2	Steam
T_{blade}/T_{cool} average	+5.14%	+2.51%	+3.61%
T_{blade}/T_{cool} max	+3.87%	+1.10%	+7.23%
T_{blade}/T_{cool} min	+2.64%	+2.48%	-2.00%
LE ε	-4.47%	-0.91%	-41.06%
TE ε	+4.37%	-2.11%	-27.34%
Average ε	-1.00%	-1.39%	-35.69%
ϕ	-14.64%	-7.15%	-10.29%

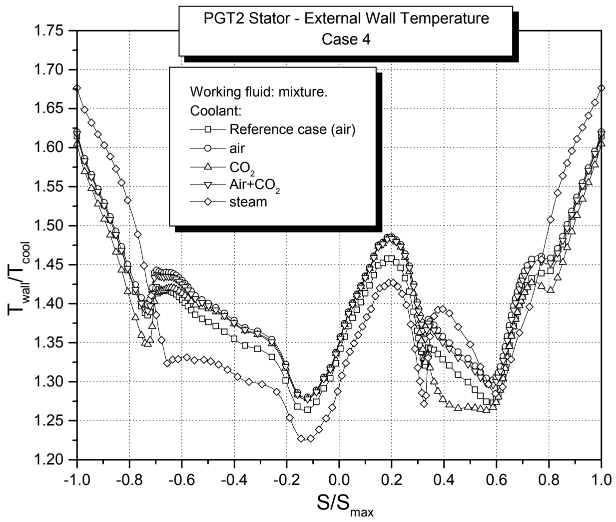

Figure 9. External wall temperature. Case 4.

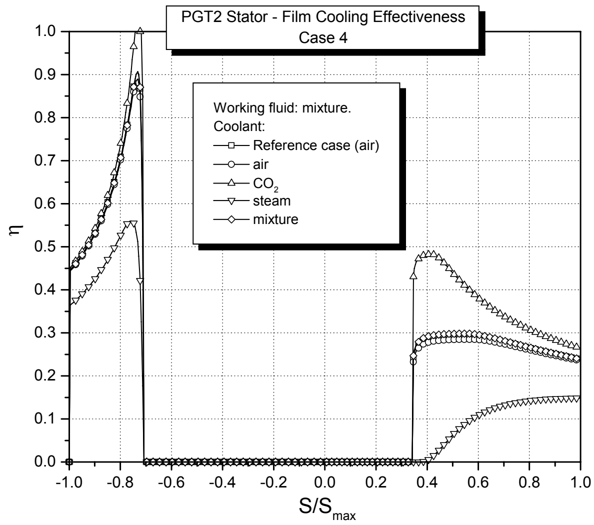

Figure 10 Film cooling effectiveness. Case 4.

CASE 3: CO_2+STEAM VS. AIR, CO_2 OR STEAM

The presence of steam in the working fluid determines a slightly higher thermal loads than case 2. This implies of course a higher blade temperature, being the only main difference. Table 6 shows come results.

Table 6. Case 3 results.

	Front Cavity			Rear Cavity		
	Air	CO_2	Steam	Air	CO_2	Steam
T_2/T_{cool}	+.81%	+.55%	-1.69%	+1.80%	+.59%	-1.11%

	Air	CO_2	Steam
T_{blade}/T_{cool} average	+5.53%	+2.88%	+3.99%
T_{blade}/T_{cool} max	+3.72%	+1.08%	+7.32%
T_{blade}/T_{cool} min	+3.28%	+3.11%	-1.42%
LE ε	-3.49%	-0.07%	-40.15%
TE ε	+5.27%	-1.58%	-26.29%
Average ε	-0.06%	-0.63%	-34.74%
ϕ	-15.79%	-8.23%	-11.38%

CASE 4: EXHAUST+CO_2 VS. AIR,CO_2, STEAM OR AIR+CO_2

In this test temperatures and external thermal loads are higher than the reference case but lower than the second case: the conclusions are almost the same as the case 2. For brevity, the Air+CO_2 fluid is referred in table 7 as Mix.

Table 7. Case 4 results.

	Front Cavity				Rear Cavity			
	Air	CO_2	Steam	Mix	Air	CO_2	Steam	Mix
T_2/T_{cool}	+.33%	+.05%	-2.0%	+.19%	+.6%	-.52%	-1.76%	.35%

	Air	CO_2	Steam	Mix
T_{blade}/T_{cool} average	+1.58%	-0.11%	+0.44%	+1.25%
T_{blade}/T_{cool} max	+0.34%	-0.61%	+3.83%	+0.17%
T_{blade}/T_{cool} min	+1.33%	+0.02%	-2.99%	+1.14%
LE ε	+0.63%	+1.40%	-39.00%	-0.77%
TE ε	+2.95%	-7.06%	-26.45%	+0.58%
Avg. ε	+1.52%	-1.90%	-34.11%	-0.25%
ϕ	-4.51%	+0.34%	-1.26%	-3.61%

Figures 9 and 10 show blade temperatures and film cooling effectiveness.

COMMENTS

The use of CO_2 as working fluid implies an increase of external heat transfer on gas turbine blade. This may require a reduction of maximum cycle temperature or an increment of coolant mass flow. Both of these conditions carry to a reduction of machine performances that must be estimated with precision in terms of plant management. Therefore it may be necessary to redesign the blade cooling system and/or the airfoil.

CO_2 behavior, as a coolant, is similar to air when used for internal cooling but it is better in the film cooling. In order to improve blade cooling, it may be necessary to redesign the cooling system, increasing the number of film cooling rows, to extend the film coverage to almost the whole blade surface.

Generally we see that steam has optimal performances in the internal cooling system while it does not seem optimal for the film cooling. It can be necessary to redesign the film injection holes if steam is used as coolant. An other solution is to use steam in close loop cooling system. This solution doesn't imply mixing losses but it requires a complete redesign of the cooling system.

At last, it is possible to use hybrid cooling system: using steam for the internal blade cooling, while film cooling is provided by injection of air or CO_2.

CONCLUSIONS

This analysis let to show and quantify the effects of coolant fluid nature on blade temperature distributions. The use of constant coolant mass flow helps in the comparison of every fluid.

The analyzed working fluids determine greater external heat transfer compared to the reference case. Cooling difficulties increase and maybe it is necessary to redesign, at least partially, the cooling system. This can represents a limit.

It is shown that CO_2 suits to film cooling whereas steam is preferable in internal cooling systems.

Finally, hybrid cooling system seems to be promising but, of course, further analyses are required.

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