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THERMAL ANALYSIS FOR NOZZLE GUIDE VANE OF A SMALL SCALE GAS TURBINE ENGINE

Emin Nadir Kaçar[1]
TEI, Tusaş Engine Industries
Eskişehir, Turkey

Haydar Aras[3]
Mechanical Eng. Department
Osmangazi University
Eskişehir, Turkey

Volkan Tatar[2]
TEI, Tusaş Engine Industries
Eskişehir, Turkey

L. Berrin Erbay[4]
Mechanical Eng. Department
Osmangazi University
Eskişehir, Turkey

ABSTRACT

Nozzle guide vane (NGV) of conventional gas turbine engine is a critical hot section part which directly faced to combustion chamber. Due to corrosive and other several fatal effects of hot gases, temperature distribution over NGV should be investigated. In this study, thermal analysis of the NGV is carried out and validated using temperature indicating paint (thermal paint). Thermal paint application can show more extensive understanding than what thermocouples can do. On the other hand, it gives an idea about exit overall temperature distribution of combustion chamber which is of interest to turbine design engineers [Chou and Lai, 2007]. Thermal painted NGV is assembled with small scale gas turbine jet engine having below 100 lbf thrust and engine test is carried out at cruise condition which is 60.000 rpm. In parallel with test, thermal analysis is performed using commercial gas turbine engine finite element analysis software. Maximum temperature of 656 ^{o}C is obtained by applying appropriate boundary conditions on NGV at 60.000 rpm. Results of thermal analysis are successively confirmed with engine test results of thermal paint.

INTRODUCTION

Turbine is the important part of a gas turbine engine which generates work. It contains static and rotating components which are critical because of being next to combustion chamber. Nozzle guide vane (NGV, static turbine part) encounters very high gas temperature, up to 1400 ^{o}C. This temperature level is beyond limits for metals and unique superalloy materials. Because of operating at very harsh environment, exact calculation of temperature distribution of the component is crucial. Correct initial conditions and boundary conditions must be defined, fluid flows and heat transfer analogies must be attempted.

After preparing a logical, reflective analysis model; it must be validated by tests. To obtain temperature distribution from test results, there are three application ways of instrumentation. These are thermal paint (object of the study), optical pyrometry or thermocouples. All three methods have advantages, i.e. thermocouple measures exact temperature of a point. On the other hand, they have some disadvantages too. Such that; surface temperature values are calculated due to thermal radiation of surfaces in optical pyrometry, but it is hard to possess specific knowledge of the emissivities of materials. Moreover, for widely used thermocouples, they can not be applied for rotating components and wiring becomes an incompatible problem also [Andral and Lempereur and Buchet and Prudhomme, 2007].

[1] Thermal Analysis Engineer, Email: nadir.kacar@tei.com.tr
[2] Thermal Analysis Engineer, Email: volkan.tatar@tei.com.tr
[3] Prof. in the department, Email: haras@ogu.edu.tr
[4] Prof. in the department, Email: lberbay@ogu.edu.tr

METHOD

In this part, the validation process of NGV will be defined and each step will be thoroughly described. Employed NGV is a component of a small scale gas turbine engine and its location can be seen in the Figure 1.

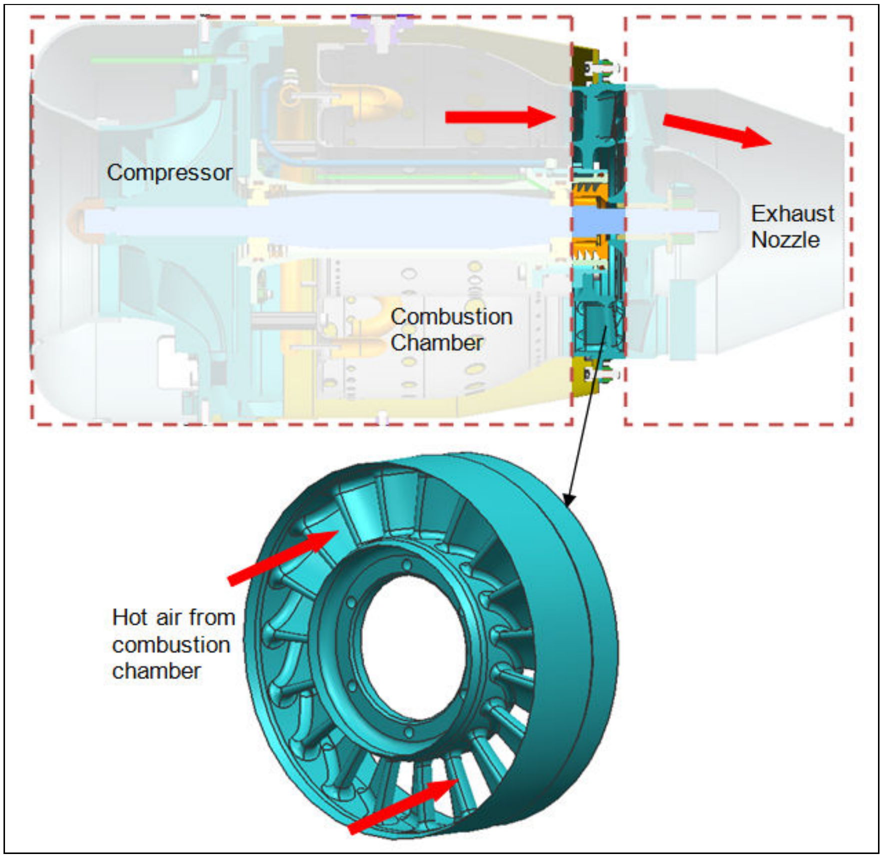


Figure 1: *The position of NGV in small scale Turbojet engine*

Thermal Analysis

In the finite element thermal analysis software; geometric definition of relevant component has been made and geometry has been meshed to appropriate element size. This analysis model consists 31748 Tetrahedron elements (Figure 2). Moreover, material type has been defined as Inconel 718.

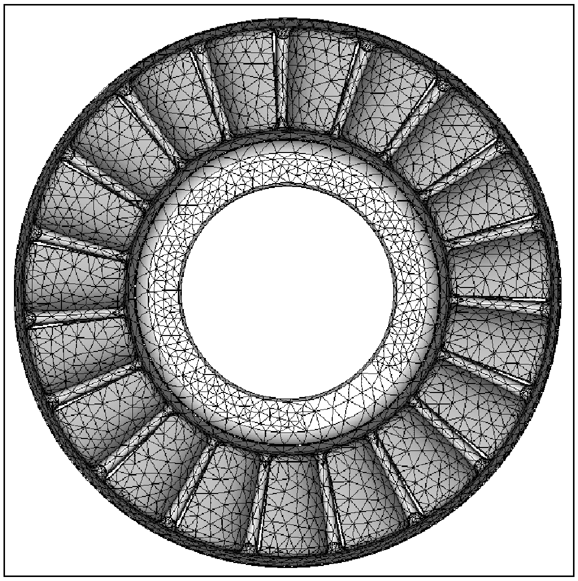


Figure 2: *Meshed geometry of NGV*

Next to the geometry meshing process, important physical phenomena must be identified. There exists convective heat transfer from flowing hot air to outside faces of the blades, and conductive heat transfer from hot disks and casing. Especially the temperature profile of combustion chamber outlet is vital and temperature distribution of hot gas has been supplied by flow analysis in Fluent, which can be seen in the Figure 3.

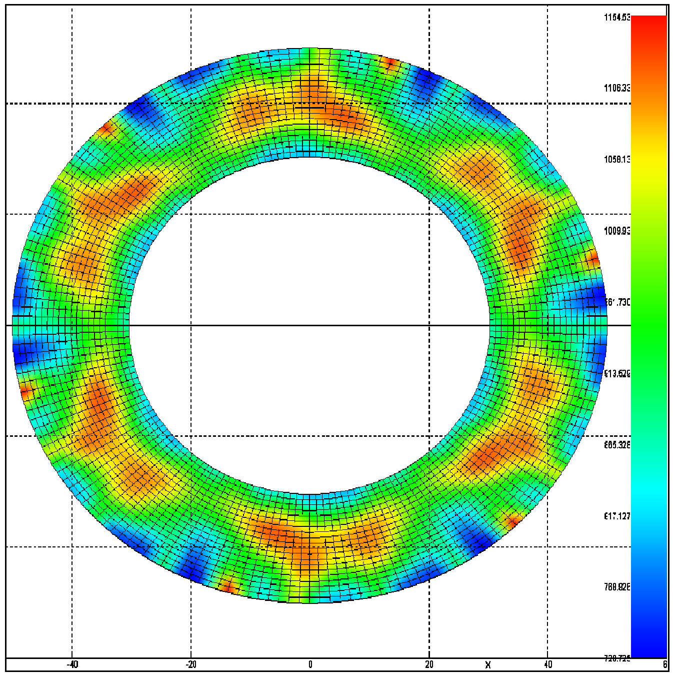


Figure 3: *The Gas Temperature distribution of Combustion chamber exit*

Radiative heat transfer affecting the leading edge and pressure side of blades are found to be very small compared to convective one and can be neglected [Siegel and Spuckler, 1998]. The basic boundary conditions including convecting zone and stream have been defined in the finite element model (Figure 4).

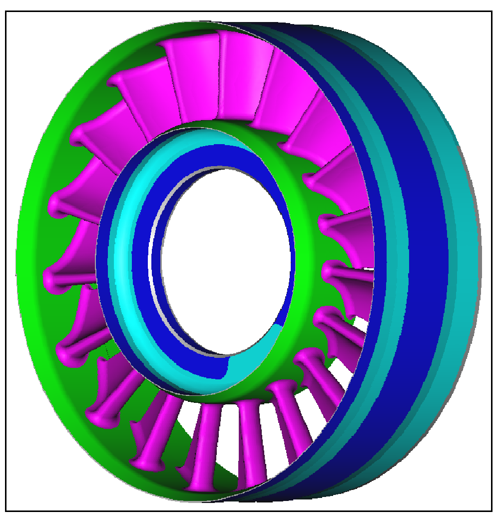
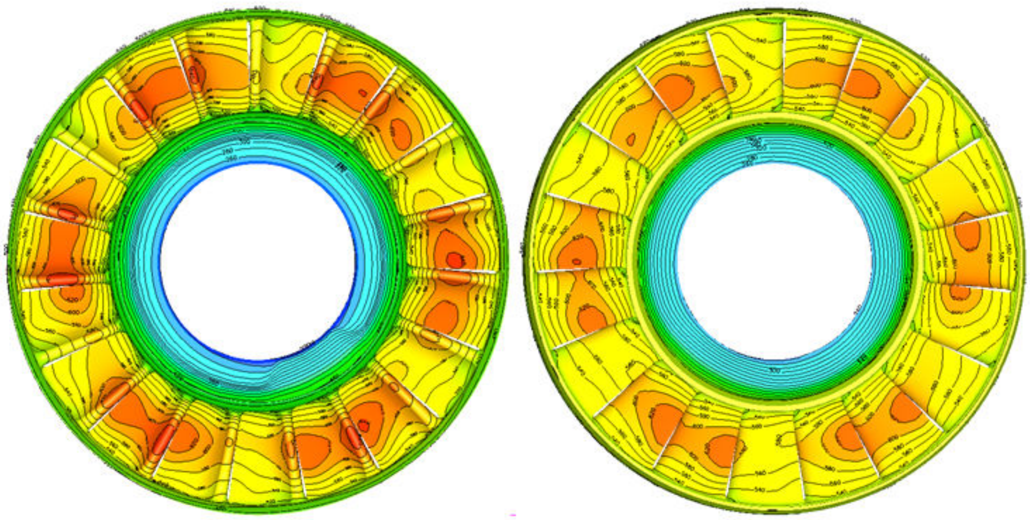


Figure 4: *The Boundary conditions of Analysis model*

Convecting zone BC which is seen as pink in the Figure 4 has been used to define convection to a known fluid temperature on a face. On the other hand, stream BC which is seen as green, is an advective flow of fluid over a portion of the boundary that is capable of absorbing energy from one location and transporting it to another. Lastly, there exist no cooling flows or cooling passage in the blades, therefore no need to define any extra BC.

At the end, the result of analysis has been achieved at 60000 rpm under steady state conditions. The metal temperature distribution and hot spots have been obtained and shown in the Figure 5.



a) *Pressure sides* b) *Suction sides*

Figure 5: *NGV thermal analysis results*

Validation

Selected thermal validation method is to use temperature indicating paint. Thermal paint undergoes permanent colour changes when subjected to particular temperatures. The final colour of the paint depends both on maximum temperature and time period it is subjected to temperature [Smith, 2002]. Thermal paint should be interpreted to comparable data with respect to analyses. This interpretation can be done using image processing styles, but in conventional applications it is done manually. Manual interpretation leads to inaccuracies due to lack of precise detection of isothermal boundaries concerning limitations to human vision [Bhalerao and Pawar, 2012].

NGV part must be cleaned and surface preparation must be done before painting. Then it can be painted with selected type of thermal paint which is KN3 as a multi-colour paint. The colour legend of the KN3 type thermal paint can be seen in the Figure 6.

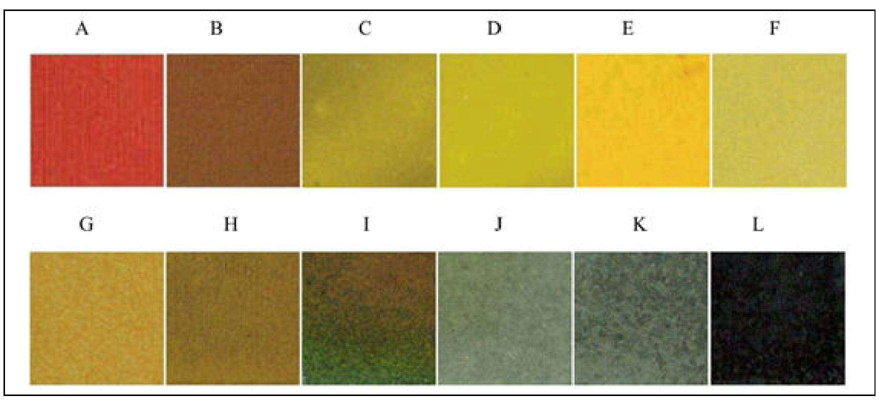


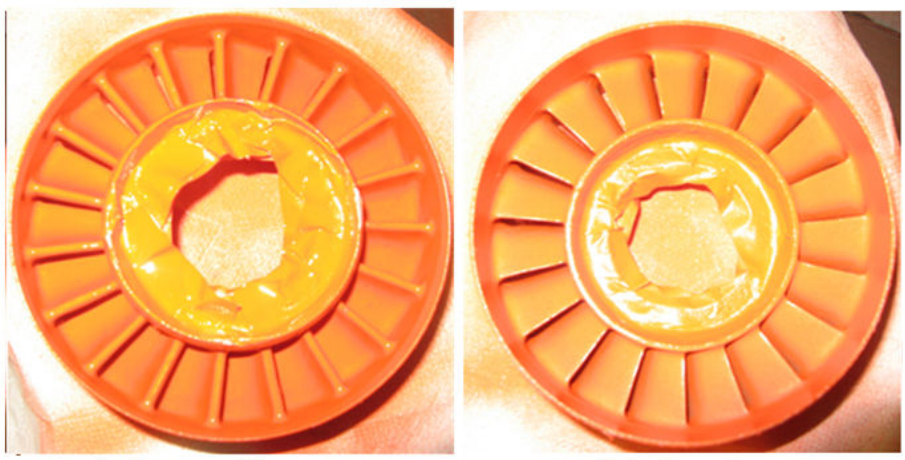
Figure 6: *KN3 Thermal paint colour legend*

It supplies results for temperature values between 430 ^{0}C and 1250 ^{0}C. For each expose time, final colours of painted components are changing, so exposition time must be strictly compatible with the time scale of paint (Table 1).

Table 1: *KN3 Thermal paint time table for color transition*

		A	B	C	D	E	F	G	H	I	J	K	L
2min	°C	<430	430	580	590	650	760	848	890	1050	1120	1155	1255
		1.29Y	1.25Y	1.06Y	1.03Y	1.04Y	0.80Y	1.16Y	1.15Y	1.20Y	0.82V	0.92V	1.68V
5min	°C	<430	430	560	570	620	750	844	885	984	1090	1115	1253
		1.29Y	1.22Y	1.09Y	1.05Y	1.09Y	0.80Y	0.85Y	1.21Y	1.19Y	0.89V	0.87V	1.62V
15min	°C	<430	430	534	555	603	742	835	868	955	1015	1068	1251
		1.29Y	1.23Y	1.10Y	1.08Y	1.05Y	0.79Y	1.00Y	1.21Y	1.21Y	1.05V	0.82V	2.01V
30min	°C	<430	430	523	543	585	732	824	850	935	985	1030	1250
		1.29Y	1.23Y	1.11Y	1.08Y	1.11Y	0.68Y	0.74Y	1.17Y	1.21V	1.23V	0.97V	2.03V
60min	°C	<430	430	513	525	570	710	788	840	900	950	1000	1250
		1.29Y	1.20Y	1.09Y	1.08Y	1.09Y	0.77Y	0.97Y	1.20Y	1.23V	1.00V	0.95V	2.15V

KN3 has been applied to the NGV part before test (Figure 7). Painted surfaces must be kindly assembled with engine. If there is fuel or oil leakage that is in contact with painted part, paint might be removed from surface which leads to a misguidance.



a) *Pressure sides* b) *Suction sides*

Figure 7: *NGV thermal paint application*

The jet engine has been tested along 10 minutes after steady state conditions are provided. The colours of thermal paint have been calibrated by the TPTT, which is supplier of the thermal paint, and shown at graphic in the Figure 8. Corresponding temperature values of the specified colours have been determined for 10 minutes using calibration graph. Using the time table and calibration graph; if the temperature exceeds 430 C^0, thermal paint indicates "B" colour. Moreover; limit for "C" is 545 C^0, "D" is 560 C^0, "E" is 610 C^0 and "F" is 710 C^0.

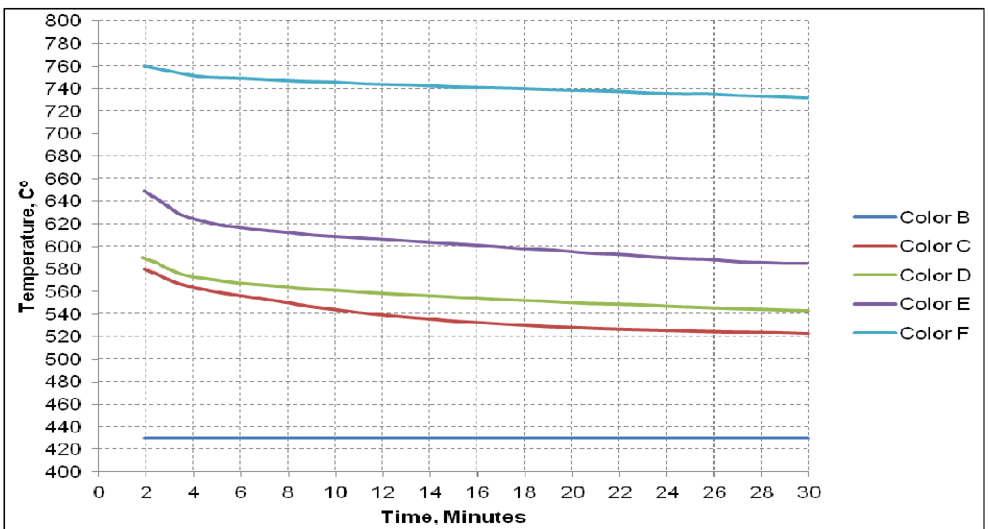


Figure 8: *KN3 paint calibration graph*

After completion of the test, NGV has been disassembled from engine and paint colour distribution has been examined (Figure 8).

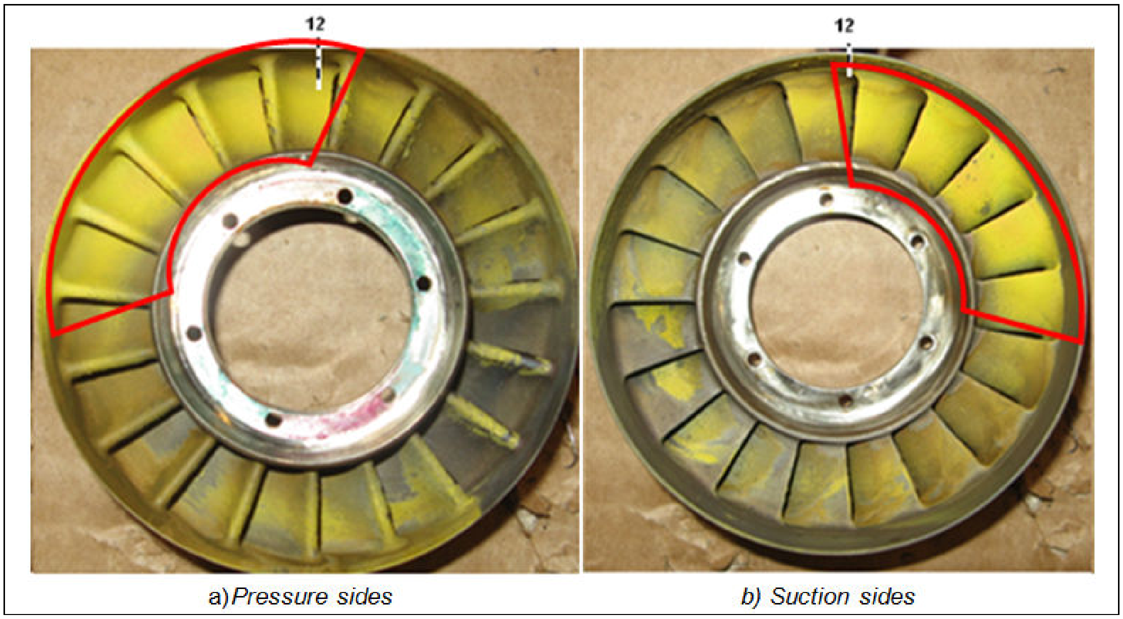


Figure 8: *NGV part test results with thermal paint*

Results can be observed in the Figure 9 in detailed version. Temperature zones have been detected regarding to their colour. In order to interpret thermal paint correctly, it has been focused on the area that still remains paint. Because, as mentioned before, paint might be removed due to fuel / oil contact with faces. "F" colour was not observed at test results; similarly maximum temperature observed in analysis is 656 C^0 which is less than 710 C^0 and it indicates "E" colour.

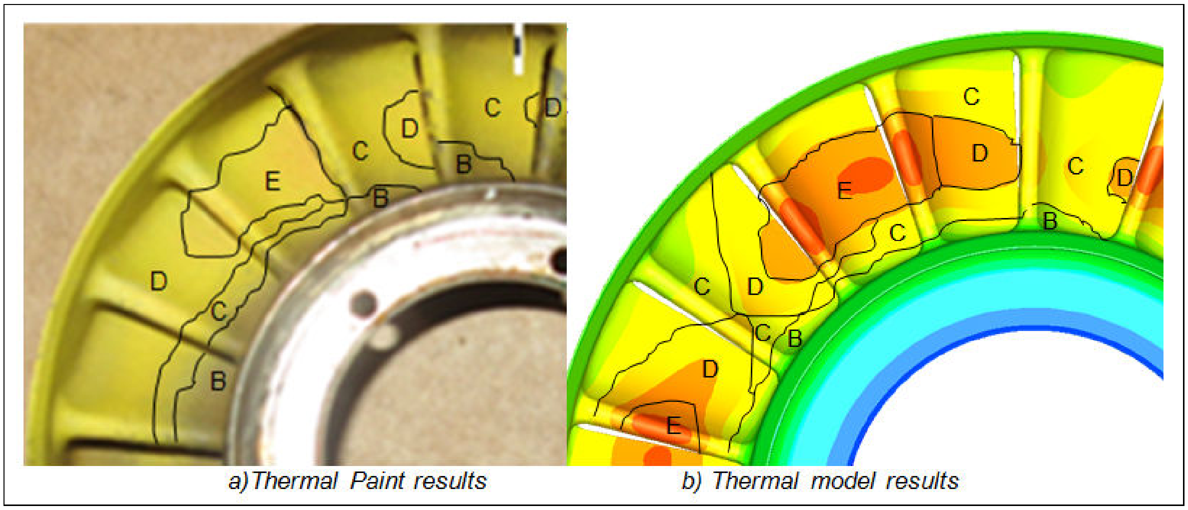


Figure 9: *Thermal paint and Analysis comparison*

"B" colour has been obtained near the hub of the Vane at the thermal analysis and also test results have verified this findings. "C" colour has been typically observed at transition region between B and D regions. "D" colour has been observed at the mid of the vane and near the trailing edge for both analysis and test results. In addition, at mid-section of fourth blade temperature value was nearly 20 C^0 higher than the test where marked as D colour. "E" colour is captured at both thermal model and test results. At some points there are hotspots in the E regions at the thermal analysis; especially on the leading edge and mid of the pressure side.
Although thermal paint results are not precise as much as thermal analysis results, they have been satisfactorily in accordance with each other.

Discussion

The NGV of a small scale gas turbine engine has been thermally validated using thermal paint since temperature range of the thermal paint on the NGV has been consistent with analysis result. Although, there are some differences between results; analysis result reflects hot spots properly.

As a result of this validation, hints about the gas temperature profile distribution have been also observed. With these findings useful feedbacks have been provided to the designers of combustion chamber;

- Evaporators must be redesigned since unburned fuel leaving combustion chamber causes thermal paint removal at blade faces.
- Exit gas temperature profile must be refined due to the non-uniform circumferential temperature distribution and also there are hot spots.

In the future, new thermal models will be analysed for the higher rpm values of the engine and improved with more test data.

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