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The Role of Thermal Barrier Coating in Maximizing Gas Turbine Engine Efficiency and Lowering CO_2 Emissions

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Dante Bonaquist, Albert Feuerstein, Leo Buchakjian and Paul Brooks[1]

Introduction

Gas turbine engines, also known as gas turbines, are heat engines that convert the chemical energy available from a liquid or gaseous fuel into mechanical energy. The mechanical energy can be used to drive rotating equipment such as generators and compressors or it can create a high velocity gas stream for aircraft propulsion. Compared to other types of engines, gas turbines have high reliability and availability, lower operating costs and high power density.

Thermal barrier coatings (TBCs) deposited on the blades of the engine's turbine section allow for higher operating temperatures leading to increased efficiency. CO_2 emissions are correspondingly reduced. We have estimated the gross reduction in CO_2 emissions enabled by TBCs applied to gas turbines by Praxair Surface Technologies to be 14.6 million MT in 2016; 7.6 million MT for aircraft engines, 7 million MT for industrial gas turbines.[2]

Gas Turbine Fundamentals

Thermodynamically, a gas turbine operates as an open Brayton cycle consisting of the following steps illustrated in Figure 1:[3]

a. Adiabatic compression of ambient air (1 to 2)
b. Constant pressure combustion of air mixed with fuel (2 to 3)
c. Adiabatic expansion of hot combustion gases (3 to 4)

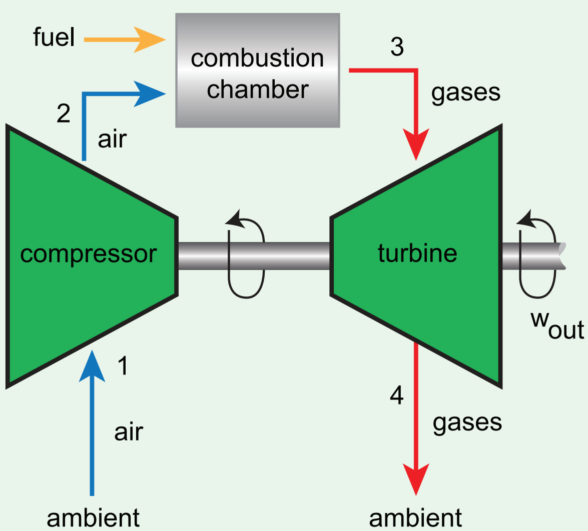

Figure 1.

The efficiency of an ideal gas turbine, defined as the ratio of useful energy derived to the available energy from the fuel, is strictly a function of pressure ratio; however, for real gas turbines, it is a function of both pressure ratio and turbine inlet temperature as shown by equation 1 below.[4]

Equation 1:

$$\text{Efficiency} = [\eta_c \eta_t \beta(1 - 1/\alpha) - (\alpha - 1)] \,/\, [\eta_c(\beta - 1) - (\alpha - 1)]$$

where:

$\alpha = (P_2/P_1)^{(\gamma - 1)/\gamma}$
$\beta = T_3/T_1$
$\gamma = 1.4$
η_c – compressor adiabatic efficiency
η_t – turbine adiabatic efficiency
T_3 – turbine inlet absolute temperature
T_1 – ambient absolute temperature

For a fixed pressure ratio, efficiency rises with increased turbine inlet temperature. This is not surprising since the maximum theoretic efficiency of any heat engine depends on the source and sink temperatures between which the engine operates; the larger difference, the greater the efficiency. Carnot cycle efficiency given by equation 2 is a function of the ratio of sink to source absolute temperature:

Equation 2: $\text{Efficiency}_{max} = 1 - (T_{sink}/T_{source})$

[1] This paper was published in April 2017. The authors are scientists at Praxair, Inc. and Praxair Surface Technologies.
[2] The claims in this paper are currently undergoing 3rd party validation. Praxair does not believe that the CO_2 equivalent emissions from the coating process and other upstream activities is substantial. Once we have the third party validation, we will update this white paper with that information.
[3] https://ecourses.ou.edu/cgi-bin/ebook.cgi?doc&topic=th&chap_sec=09.1&page=theory
[4] Smith, J. M. and H. C. Van Ness, *Introduction to Chemical Engineering Thermodynamics*, 2nd ed., McGraw Hill Book Company, NY (1958) p 291-292.

Material Science Enables Higher Efficiency

Turbine inlet temperature is limited by the allowable turbine blade temperature which is a function of the blade metallurgy. Over the years, gas turbine designers have increased the allowable turbine blade temperature by employing progressively higher temperature alloys. Today specialized high temperature nickel-based superalloys are used in both aircraft engines and industrial gas turbines.[5] Blade cooling technology has also made increases in turbine inlet temperature possible.[6] Heat is removed by circulation of cooling air through passages built into the turbine blades. To provide additional cooling, some of the cooling air is allowed to escape though holes in the blade. This air creates a film on the surface of the blade thereby limiting the transfer of heat from the hot gas to the blade.

Further increases in turbine inlet temperature have been made possible by the development of thermal barrier coatings (TBCs). TBCs are applied to the exterior surface of the turbine blades. The additional resistance to heat transfer introduced by the TBCs, when combined with cooling allows turbine inlet temperatures that approach or exceed the melting point of the superalloy.[7] See Figure 2.

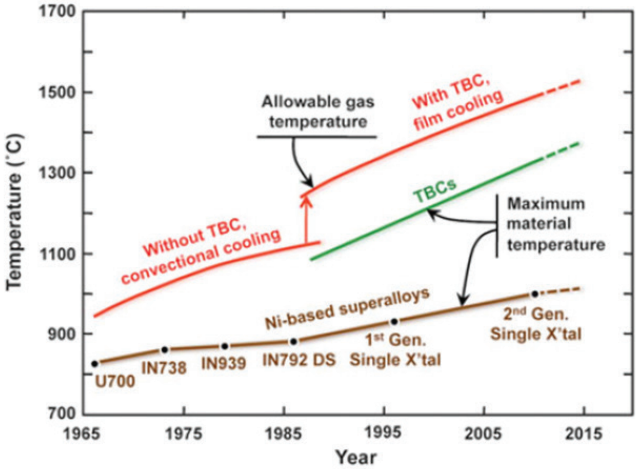

Figure 2.

Typical TBC systems consist of a MCrAlY (M=Ni,Co) or a diffusion aluminide bond coat which forms an alumina layer (thermally-grown oxide, TGO) on to which is deposited a yttria-stabilized zirconia (YSZ) TBC. The TBC can be deposited by plasma spraying, or electron beam physical vapor deposition (EBPVD). The EBPVD coatings are used for the most demanding applications, such as the leading edges of airfoils. The use of TBCs can achieve temperature differentials across the coating of as much as 175 deg. C.[8]

Estimating Gas Turbine Efficiency Increase Enabled by TBCs

Figure 3 shows the improvement in gas turbine efficiency made possible by TBCs as a function of gas turbine pressure ratio and temperature differential across the coating. For the purposes of this figure, the adiabatic efficiency of the compressor and turbines sections are each assumed to be 90%. Ambient temperature is set at 20 deg. C while based case turbine inlet temperature is fixed at 1,400 deg. C.

Pressure ratios for modern industrial gas turbines are typically in the vicinity of 20 while those for turbofan aircraft gas turbine engines are around 40. For the purposes of estimating the CO_2 emissions reductions attributable to TBCs, we will use an efficiency improvement of 2.6% which corresponds to a pressure ratio of 30 and a differential temperature of 150 deg. C.

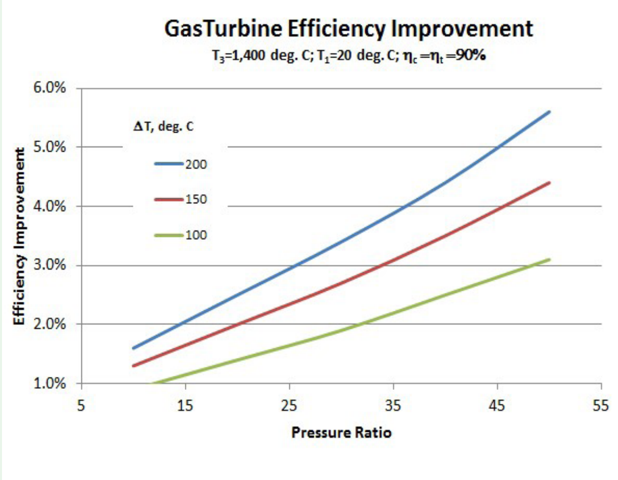

Figure 3.

[5] https://cdn.intechopen.com/pdfs-wm/22905.pdf
[6] https://www.witpress.com/Secure/elibrary/papers/HT08/HT08014FU1.pdf
[7] Clarke , David R., Matthias Oechsner , and Nitin P. Padture , "Thermal-barrier Coatings for More Efficient Gas-turbine Engines", MRS Bulletin, Vol. 37, October 2012.
[8] Stiger, M. J., N. M. Yanar, M. G. Topping, F. S. Pettit, and G. H. Meier, "Thermal Barrier Coatings for the 21st Century", Z, Met.k.d., 90 (1999) 1069-1071.

Estimate of Aircraft Gas Turbine CO_2 Emissions Reduction

Table 1

Airplanes in service 2015 to 2035		
	2015	**2035**
Large wide body	740	700
Medium wide body	1,640	3,690
Small wide body	2,660	6,060
Single aisle	14,870	32,280
Regional Jets	2,600	2,510
Total	**22,510**	**45,240**

According to Boeing data, 22,510 commercial jet aircraft with more than 30 seats were in service worldwide in 2015[9]. This number excludes turbo props, biz jets and military aircraft. Table 1 shows the breakdown of current jet aircraft into the different airframe sizes.

For the estimate of the CO_2 savings by TBC technology we use the following key assumptions:

- Based on the airframe size and model year and internal marketing data we estimate the share of aircraft with TBC technology in the hot section to 80%. This can include TBC's on HPT airfoils, vanes, combustors and shrouds.
- The average distance traveled per US commercial aircraft is 1,750,000 miles with an average CO_2 emission of 53lbs per mile.[9]
- The average efficiency savings by TBC technology are 2.6% as calculated before.
- Based on PST internal marketing data the current PST share in WW advanced TBC coating technology of aero engines is 39%. In applying this number to the WW fleet there is an uncertainty about very old legacy engines. We have tried to cover for this with the assumption made above, that only 80% of the fleet uses TBC technology.

With these assumptions the total aircraft CO_2 avoidance due to PST's TBC technology is 7.6 million metric tons. The aircraft CO_2 avoidance calculation is shown in more detail in Table 2.

Table 2

Aircraft CO2 Savings by PST TBC Technology			
	2016	**Units**	**Reference**
Number of Commercial Aircraft in Service	22,510		Boeing data[10]
Share of Commercial Aircraft with TBC Technology	80%	percent	Estimate
Number of Commercial Aircraft in Service with TBC's	18,008		
Avg. distance travelled per US airplane annually	1,750,000	mi	http://blueskymodel.org/
CO_2 emission per mile	53	lbs/mi	http://blueskymodel.org/
CO_2 emission per airliner	92,750,000	lbs/yr	
Efficiency savings by TBC technology	2.6%	percent	
Total MT avoided per aircraft	1095	MT/yr	
Total WW CO_2 avoidance by TBC technology	**19,715,537**	**MT/yr**	
PST share in WW Aircraft TBC	**39%**	**percent**	**Internal marketing data**
Total PST contribution to CO_2 avoidance MT	**7,689,059**	**MT**	

[9] http://blueskymodel.org/
[10] Boeing Current Market Outlook presentation, Farnborough 2016

Estimate of Industrial Gas Turbine CO_2 Emissions Reduction

The estimate of the CO_2 emission reduction for the worldwide installation of Industrial gas turbines is based on the following data sources and assumptions:

- Based on publications from the main power generation gas turbine producers – GE, Alstom, Siemens, Ansaldo, Mitsubishi, Solar Turbines and Hitachi[11]; the total number of gas turbines installed worldwide in 2016 is approximately 20,000.
- The analysis of the worldwide power generation gas turbine installation base yields 46 MW as the median power of a turbine.
- Assuming 4,000 operating hours p.a. we estimate the annually generated electric energy by power generation gas turbines at 3.680 trillion kWhrs. For reference: the worldwide electricity generated in 2017 by petroleum and natural gas is estimated by EIA at 6 trillion kWhrs. We attribute this higher number to combined cycle plants, which use additional steam turbines not utilizing TBC technology.
- For the calculation of the related CO_2 emission savings we use petroleum as fuel basis with a consumption of 0.07 gal per kWhr.[12]
- For the TBC efficiency related fuel savings we assume again a number of 2.6%, as estimated before. We think that this is a reasonable assumption because a significant percentage of current power generation GT technology is based on aero engine technology (Aero derivatives).
- Furthermore, based on internal marketing data we estimate the percentage of gas turbines coated with PST TBC technology as 10% of the WW volume.

With these assumptions we calculate the annual CO_2 savings related to PST TBC technology as 7 million metric tons.

Table 3 shows the calculation of the CO_2 savings in more detail.

Table 3

Power Generation GT CO2 savings by PST TBC Technology			
		Unit	**Reference**
Number of WW installed industrial gas turbines for power generation	20,000	units	Ref 11
Average power per gas turbine	46	MW	Ref 11
WW GT Power installed	920,000	MW	
Operation hours per year	4,000	hrs	Assumption
Total WW GT electricity generated	3,680,000,000	MWhrs	
Petroleum fuel consumption in gal per kWhr	0.07	gal/kWhr	Ref 12
Annual fuel consumption (gal)	257,600,000,000	gal	
Weight per gal petroleum	7.21	lbs/gal	
Annual fuel consumption (lbs)	1,857,296,000,000	lbs	
Conversion factor lbs to MT	2,204.62	lbs/MT	
Annual fuel consumption (MT)	8,42,456,296	MT	
Efficiency savings (%) by TBC technology	2.60	percent	Assumption
Calculated Fuel TBC savings (MT)	21,903,864	MT	
PST share in WW IGT TBC	10%	percent	Internal Marketing data
Fuel savings (MT) by PST TBC Technology	**2,190,386**	**MT**	
3.2lb of CO2 per lb of fuel combustion	**3.2**	**lb**	**Literature data**
CO2 savings (MT) by PST TBC Technology	**7,009,236**	**MT**	

[11] PST internal marketing data based on data from GE, Alstom, Siemens, Ansaldo, Mitsubishi, Solar Turbines and Hitachi.
[12] https://www.eia.gov/tools/faqs/faq.cfm?id=667&t=3

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USA
Praxair, Inc.
10 Riverview Drive
Danbury, CT 06810
Phone: 1-800-PRAXAIR
1-800-772-9247
www.praxair.com

Canada
Praxair Canada, Inc.
1 City Centre Drive, Suite 1200
Mississauga, ON L5B 1M2
Canada
Phone: 905.803.1600
www.praxair.com

Mexico
Praxair Mexico S.A. de C.V.
Biologo Maximino Martinez
No. 3804
Col. San Salvador Xochimanca
02870, Mexico D.F.
Phone: +52(55)5354.9500
www.praxair.com.mx

South America
White Martins Gases
Industriais Ltda.
Avenida das Américas, 3434,
Bloco 7, 6th fl.
22640-102 Rio de Janeiro
Brazil
Phone: + 55 (21) 3431.2000
www.whitemartins.com.br

Europe
Praxair España S.L.
c/ Orense, 11
E-28020 Madrid
Spain
Phone: +34(91)453.3000
www.praxair.es

Scandinavia
Praxair Scandinavia AS
PB 23 Haugenstua
0915 Oslo
Norway
Phone: 04277 (+47 21 49 34 34)
www.praxair.no

India
Praxair India Private Limited
"Praxair House"
No. 8, Ulsoor Road
Bangalore –560 042
India
Phone: +91.1800.425.8077
www.praxair.com/india

China
Praxair Asia Inc.
21 fl., Eton Place
69 Dongfang Road
Pudong, Shanghai 200120
PRC
Phone: +86(21)2894.7000
www.praxair.cn

Praxair Korea Co. Ltd
943-19, Shinan Building 16th fl.
Kangnam-gu, Daechi-dong
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Korea
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info@praxair.com

Telephone:
1-800-PRAXAIR (1-800-772-9247)
(716) 879-4077

Fax:
1-800-772-9985
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