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Journal of the IDGTE

Power Engineer

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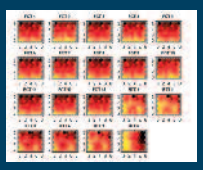

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the independent technical forum for power generation

March 2018
Volume 22 Issue 1

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President's message

Tony Hancock, President

2018 certainly started with an early shock - the "Beast from the East" - and one can only imagine the outcome for the UK's power generation industry as we had forecasts of gas shortages, which were then found to be more than sufficient, the usual chaos with transportation and power disruptions, but with ample wind for the windfarms and even a lot of sunshine for the solar producers! Quite an extraordinary sequence of events as far as I recall.

The Strategy Review Team held a teleconference in January to review progress. A number of options are now being explored and discussed and proposals will be reported back to the Trustees by mid year.

Mike Raine, our Director General, and I had a very useful meeting with David Loosely, Chief Executive of the Institute of Marine Engineering, Science and Technology at the end of February. There are several areas of mutual interest and we discussed how the IMarEST had been able to successfully increase membership numbers in recent years and where there may be mutual interest in seminars and technical presentations and conferences etc. David was very open and shared their experience. We will be looking further into joint events later this year.

John Platt, Past President, attended the CHAIN event at Manchester University, also in February. This is the third time this event has been held and we have had a presence at each and it has been very well attended. Mark Cornforth of Maktec Marine, a recent new member of the IDGTE was also present, and they discussed Maktec's involvement with the Britannia Challenge, which proved a very popular session. You can read more about this in the article on page 3.

I was reminded that we had two of our overseas members, of our MENA branch, from Carthage Power, attend the Gas Turbine Conference late last year and we look forward to hearing more about activities from the Branch. There is also work in hand with regard to setting up another overseas Branch. We are working with the overseas interests and have support from Cranfield University also.

Looking ahead we are now finalising arrangements for the 71st Annual Technology Seminar and Luncheon on 3rd May, again at the Grange Tower Bridge Hotel. This has become a strong event, with excellent presentations, a fine lunch and highly regarded speakers.

"This has become a strong event, with excellent presentations, a fine lunch and highly regarded speakers."

Tickets are now be available. For more information and to book your ticket(s) go to www.idgte.org/annualluncheon.html
Alternatively call Sandra or Carole on 01234 214340.

Later this year we are looking towards a one day Technical Seminar in September with the current theme around the latest emissions issues now impacting smaller engines, and possibly to address the often overlooked concerns over noise abatement. We would be very interested in contributions from our members on either of these topics.

Further ahead we are also scoping ideas for a November Conference centred on reciprocating engines. Any ideas or contributions on specific topics would be welcomed and will help us to build the conference theme.

Easter comes early this year, so on a personal note I hope it heralds an early change to more Spring like days! ■

British from start to finish

Portsmouth-based Team Britannia looks forward to their attempt to break the round the world powerboat record, as onboard journalist Clive Tully explains.

There can be few record-attempting projects like Team Britannia that have been nine years in gestation – indeed, if you add the original aim to break the round the world powerboat record in Spirit of Cardiff (which didn't quite make it), you're talking about a dream nearly 20 years in the making! But through all of this, Portsmouth engineer and businessman Alan Priddy has remained doggedly focussed.

Team Britannia "Excalibur"

"It would have been a lot easier if we were trying to get sponsorship for a sailing attempt," he admits. *"Powerboats don't have such a broad appeal, particularly when it's just one racing against the clock."* The official UIM record of 60 days 23 hours 49 minutes has been held by New Zealander Pete Bethune and his boat 'Earthrace' for 10 years, with the previous record held by the British boat 'Cable & Wireless Adventurer' – also for 10 years – which illustrates the difficulty compared with sailing records which tumble far more frequently.

Alan Priddy with one of the boat's two diesel engines

While the 2002 'Spirit of Cardiff' attempt in a 33 foot RIB entailed a tortuous route around the north Pacific rim with a total of over 30 refuelling stops, Priddy's new boat 'Excalibur,' under construction at ABC Marine on Hayling Island, is nearly three times the size, and will

It's this big! Alan Priddy inside the boat.
Credit: Chris Davies

complete the 23,000 mile circumnavigation with just six or seven refuelling stops. Key to this incredible range is a unique hull design claimed to be 30% more fuel efficient than anything else afloat, and a massive 30,000 litres fuel capacity.

It all gets rather more exciting when you include the Clean Fuel factor. Alan Priddy's development of Clean Fuel has taken place in parallel with the engineering excellence of Team Britannia. Mixing water with diesel might sound like the recipe for seized cylinders, but the patented Clean Fuel process cuts pollution dramatically. Particulate Matter (PM) and various Nitrous Oxides are the stuff of smog in every major city throughout the world, and governments are aware that this pollution is responsible for thousands of chronic illnesses and premature deaths every year.

CLEAN FUEL

Symbiotic relationship - Clean Fuel

"Team Britannia will showcase the benefits of Clean Fuel by mixing it for use as we go," explains Priddy. *"The Clean Fuel emulsion, purified seawater and diesel are piped into the mixing unit – about the size of a small sewing machine – and the resultant blend pumped into a small holding tank ready to feed the two Fiat Power Train engines. Mixing on the fly gives us the maximum range possible from each 30,000 litres fill of fuel. Data will be fed to Team Britannia's website so people can track fuel usage, engine temperatures and lots more, which we hope will be of interest to scientists and techno-geeks alike."*

Team Britannia gathering in London
Credit: Chris Davies

While the core of Priddy's crew encompasses people who have accompanied him on previous adventures, 5 of the 12 places are for former members of HM Forces sponsored by Blesma, the charity for limbless ex-servicemen. They include Lee Spencer, a former Royal Marine who next year will attempt to row solo across the Atlantic, and Daisy Coleman – invalided out of the Royal Artillery after tours in Iraq and Afghanistan – and now carving an exciting career as a champion P1 powerboat racer.

'Excalibur' is close to completion, with launching expected late spring or early summer, and sea trials including one or two record attempts before the big trip in October 2018. Team Britannia's route will cross the Atlantic, Pacific and Indian oceans, transit the Panama and Suez Canals, beginning and ending in Gibraltar – making an epic voyage which will be truly British from start to finish! ■

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Yorkshire company takes on the world record

Hydro Diesel's Alan Priddy with Maktec Marine's Mark Cornforth with Excalibur under construction

Yorkshire based Maktec Marine is to provide technical support for the engine fuel and oil performance for Team Britannia, the organisation behind the latest record attempt for sailing around the world in the fastest time; led by well-known ocean adventurer Dr Alan Priddy. Maktec Marine founder Mark Cornforth said the challenge is to beat the current world-record holder, New Zealander, Pete Bethune's time of 60 days 23 hours 49 minutes for the 23,000 mile voyage. The attempt will be made in a specially designed 80ft powerboat, which is being built in the UK, ahead of the world-record attempt in 2018.

IDGTE member, Mr Cornforth said *"The world-record effort is taking on even greater significance as the vessel will be powered by a ground-breaking new eco-fuel called Hydro Diesel. The fuel has been developed over the last two years and in tests Hydro Diesel dramatically reduces harmful emissions such as particulate matter and nitrogen dioxide when used in existing diesel engines without modifications."*

"Maktec has developed its engine expertise working on all kinds of vessels and engines around the world over the last 20 years" said Mark *"and we are absolutely delighted to be chosen as technical engine support and fuel oil performance advisers for this incredible record attempt and longer term as the distributor of Hydro Diesel. The challenge reflects Maktec's passion to make engines greener, less harmful and more energy efficient. At Maktec we know the diesel industry at sea and on land has to find urgent solutions to become greener. Hydro Diesel is designed to work on existing diesel engines in ships, cars and other vehicles."* ■

Using the fuel flexibility of gas turbines to decarbonise power generation

Michael Welch
Industry Marketing Manager
Siemens AG

Abstract

The power generation industry has a major role to play in reducing global greenhouse gas emissions, and carbon dioxide (CO_2) in particular. There are two fundamental ways to reduce CO_2 emissions from power generation: improved conversion efficiency of fuel into electrical energy, and switching to fuels with lower carbon contents.

Gas turbine generator sets, whether in open cycle, combined cycle or cogeneration configuration, offer some of the highest efficiencies possible across a wide range of power outputs. With natural gas, the fossil fuel with the lowest carbon content, as the primary fuel, they produce among the lowest CO_2 emissions per kWh generated. It is though possible to decarbonise power generation further by making use of the fuel flexibility of the gas turbine, by fully or partially displacing the natural gas used, or by switching to lower carbon fuels such as propane or LPG in place of diesel and fuel oils.

In a number of industries, an off-gas containing hydrocarbons is produced which is often flared, creating CO_2 emissions. These off-gases can be used to generate power locally in decentralised power plants, displacing the need to import power from centralised fossil fuel power plant and thus decreasing global CO_2 emissions. Alternatively, 'surplus' renewable power generation can be used to create hydrogen, which can be stored and used as a gas turbine fuel when renewable power generation is low, displacing all or a percentage of the fossil fuel used. As hydrogen is a zero carbon fuel, it offers the opportunity for gas turbines to produce zero carbon electricity.

This paper examines the potential to use a wide range of unconventional low carbon fuels and hydrogen in industrial gas turbines, and reviews operational experience gained in various industries and the future potential developments for further decarbonisation of power generation.

Introduction

Carbon dioxide (CO_2) is the largest contributor to man-made Greenhouse Gas (GHG) emissions. Approximately 75% of CO_2 emissions come from the combustion of fossil fuels to provide energy, with the power generation industry alone contributing a significant portion of these emissions (around one third of all CO_2 emissions in the European Union come from power generation).

Table 1 lists the six key GHG contributors and their global warming potential expressed as CO_2 equivalent over various time horizons. CO_2, CH_4 and N_2O are all directly associated with power generation through the combustion of fossil fuels – CH_4 being present as unburned fuel in the exhaust gases of natural gas-fired generator sets and boilers.

	20 Years	100 Years	500 Years
CO_2	1	1	1
CH_4	56	21	6.5
N_20	280	310	170
HFC-23	9,100	11,700	9,800
HFC-32	2,100	650	200
SF_6	16,300	23,900	34,900

Table 1 GHG global warming potential expressed as CO_2 equivalent

CO_2 emissions from fossil fuel power generation depend on two factors: the type of fuel used and the efficiency of conversion of the chemical energy in the fuel into electricity. It is therefore apparent that the lower the carbon content of the fuel and the more efficient the conversion process, the lower the CO_2 emissions.

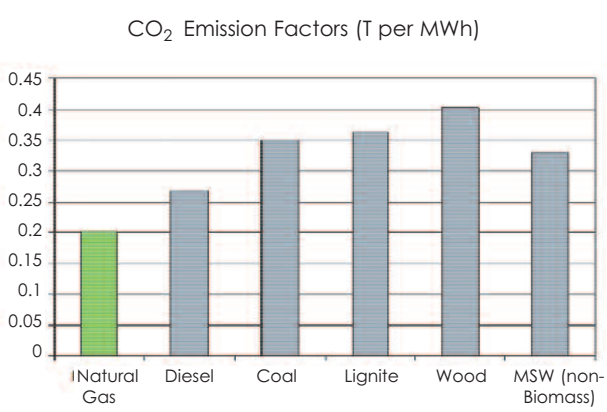

Figure 1 CO_2 emissions factors for fuels commonly used in power generation expressed as tonnes per MWh

Figure 1 shows the CO_2 emissions in tonnes per MWh for commonly used fuels in the power generation industry, with natural gas clearly being the fuel with the lowest CO_2 emissions.

Once the fuel has been selected, the efficiency of power generation then determines the final CO_2 emissions: the higher the conversion efficiency of fuel to useful energy, the lower the CO_2 emissions.

The conversion efficiency depends on the configuration of the power plant or energy centre, the fuel used and on scale of energy conversion: large plants are usually more efficient than smaller ones, gas-fuelled plants typically more efficient than fuel oil or coal-fired power plants. Open cycle units tend to be relatively inefficient, so many power plants employ combined cycle technology, where the waste heat in the exhaust gases of the gas turbines (or reciprocating engines) is used to produce steam to drive a steam turbine generator set to boost power output and improve the overall efficiency of power generation. While most GHG emissions come from pure power generation sources, it should be noted that many industries and buildings have both power and process heat needs and in many cases have installed their own power generation systems for economic or security of supply reasons.

Cogeneration, or Combined Heat and Power (CHP), utilises the waste heat from power generation to produce the process heat required, enabling very high overall energy efficiencies to be achieved, reducing CO_2 compared to e heat and power production. It should be noted though that if power is generated in central power plant and transmitted to consumers through power lines, losses occur across the transmission and distribution network reducing the effective efficiency of the centralised power generation system typically installed today. The typical range of energy efficiencies achievable from the various configurations is shown in Figure 2.

From Figures 1 and 2 it can be concluded that the most energy efficient plant – and hence lowest CO_2 emitters - are natural gas-fuelled cogeneration schemes. If a heat load is not available, then combined cycle configurations produce the lowest GHGs although CH_4 emissions as unburned fuel can have a major impact on GHG emissions: some power generation technologies, such as Otto Cycle gas engines, have high levels of unburned fuel in the exhaust gases (methane slip) when operating on natural gas fuel, which increases total GHG emissions to levels approaching those of a power plant operating on diesel fuel (Figure 3).

Gas turbine combustion systems

While the combustion system on a gas turbine has no direct impact on CO_2 emissions, it has an indirect impact due to the types of fuel that can be utilised.

Gas turbines were originally developed with diffusion flame combustion systems, relatively simple combustors with a wide

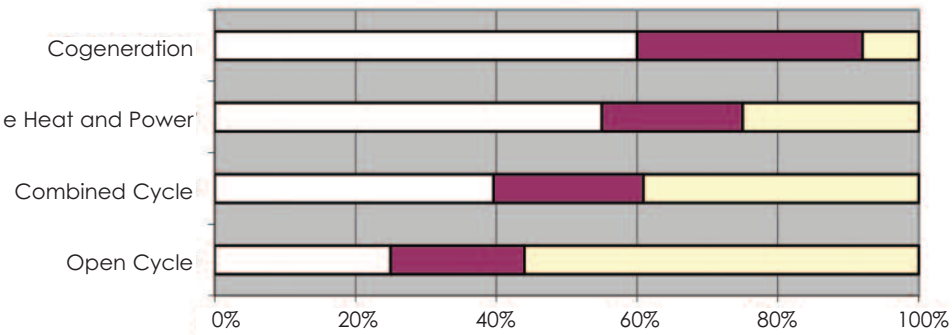

Figure 2 Typical ranges of overall energy efficiencies for different power plant configurations

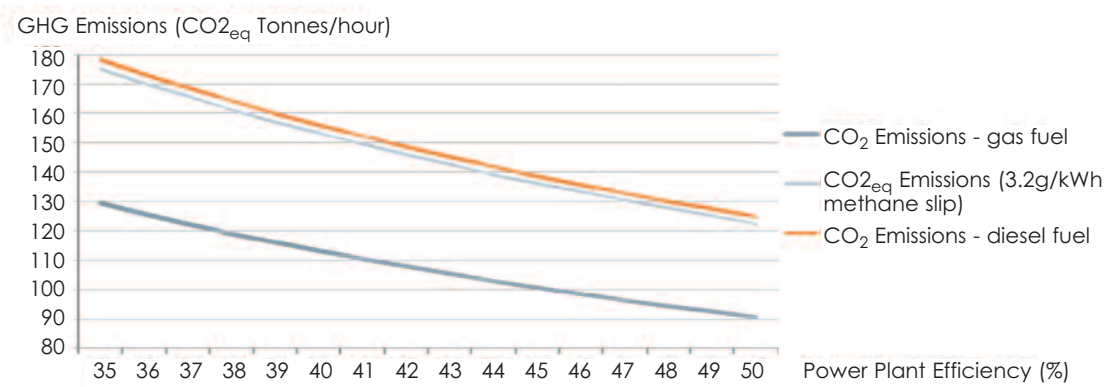

Figure 3 Impact of efficiency and methane slip on GHG emissions

range of fuel flexibility. However, such systems produced high levels of NOx, CO and unburned hydrocarbons (UHC), pollutants that create environmental and human health problems. Environmental legislation required reduction of these pollutant emissions, so gas turbine manufacturers developed 'wet' NOx reduction technology, using water or steam to reduce NOx, but this technique increased CO emissions.

As legislation required lower and lower levels of NOx and CO emissions, manufacturers developed Dry Low Emissions (DLE) combustion technology to meet these requirements. Predominantly based on lean pre-mix technology, DLE combustors produce very low levels of NOx, CO and UHCs but with less fuel flexibility than could be achieved in diffusion flame combustors.

The ability of a gas turbine combustor to burn a fuel depends on a number of factors associated with the fuel composition, but the key ones are:

- Wobbe Index: a measure of the energy content of the fuel
- Flame speed and flashback potential
- Dew point

DLE combustors were originally developed for operation on pipeline quality natural gas fuels, and then a liquid fuel capability was added as diesel is commonly used as a back-up fuel for natural gas. Combustor developments were undertaken to expand the range of gaseous fuels that could be accepted, and technologies developed that allow gases with high inert contents or higher hydrocarbons such as ethane and propane to be accepted in DLE combustors.

One of the challenges with higher hydrocarbons is that the flame speed is faster than natural gas, leading to the possibility of flashback where combustion occurs at the burner tip or within the fuel injector causing rapid component damage. Modifications to the burner and fuel system are required to ensure the flame is correctly positioned in the combustion chamber. Hydrogen has a higher flame speed still – about 8 times as fast as methane, the key component in natural gas – creating even greater potential flashback issues.

The Wobbe Index determines the mechanical design of the fuel injectors and injector hole sizing. To maintain the correct air and fuel flows and mixing as fuel composition changes, it may be necessary to make subtle adjustments to the fuel injection hole sizing or swirler geometry. This can lead to limitations on the range of fuels that can be burned using a specific burner design, requiring multiple burner designs to cover a similar wide fuel range as an older diffusion flame burner.

Fuel switching

The simplest way to reduce CO_2 emissions from power generation is, as can be seen from Figure 1, to switch from a high carbon content fuel, such as coal, to a low content fuel such as natural gas. This is exactly what has been happening in the power generation industry across the world.

However, in many locations natural gas is not available or its supply cannot be guaranteed despite growing volumes of and access to Liquefied Natural Gas (LNG). In these locations Light Fuel Oil (LFO) or Heavy Fuel Oil (HFO) are commonly used as the primary or back-up fuels due to their competitive costs. But HFO and LFO are high carbon content fuels (Figure 4), which also have other detrimental environmental characteristics. One option would be to utilise ethane, propane or other LPG blends as the primary or back-up fuels, all of which emit less CO_2 when combusted compared to fuel oils.

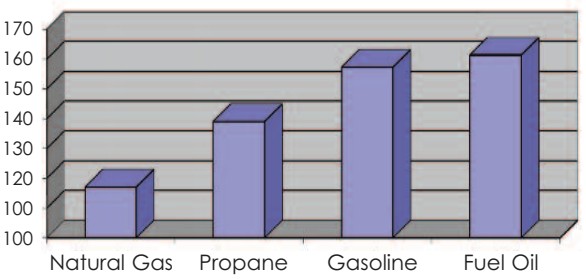

Figure 4 CO_2 emission comparison in lb CO_2 per million Btu for different fuel types (source US Energy Information Administration)

While using LPG as a gas turbine fuel is not a new phenomenon, switching from HFO or LFO to LPG is becoming of increasing interest as the prices of LPG have dropped dramatically over recent years due to increased natural gas production, especially in the USA. LPG fuelled gas turbines were installed many years ago in North America, Europe and Japan, but more recently gas turbines have been installed in China, Latin and Central America and West Africa for operation on LPG as power demand grows faster than natural gas can be supplied or as a back-up fuel in case of natural gas supply failure.

Figure 5 7MW class gas turbine installed in Japan that operated on gasified LPG

As well as lower CO_2 emissions, LPG has other environmental benefits compared to fuel oils with no sulphur and lower NOx emissions, while unlike methane, propane and butane are not considered GHGs in case of a leak. LPG also has no shelf life making it an ideal back-up fuel, whereas in hot climates the shelf life of diesel can be as low as 6

months. However, propanes and butanes burn with a hotter flame than natural gas, leading to increased NOx production compared to pipeline quality natural gas. DLE capability has been developed on some gas turbine models to address this issue, and NOx levels achieved somewhere between those associated with natural gas and diesel. There is an issue though in that LPG may have a variable fuel composition depending on where it is purchased.

Commercially available LPGs vary from 100% propane through various propane/butane blends to 100% butane. DLE combustion capability to date has concentrated on 100% propane or SNG (a blend of propane and air designed to bring the Wobbe Index into the same range as pipeline quality natural gas) as the higher hydrocarbons have a greater propensity to encourage flashback. Some development work has been undertaken on LPGs predominantly comprised of propane with up to 40% butane content and DLE combustors are now commercially available for such blends.

Utilising waste gases

In many industrial – and natural – processes, a gas is created as the by-product of the process. In the iron and steel industry this could be Blast Furnace Gas (BFG) or Coke Oven Gas (COG), landfill gas from the waste management industry, or off-gases from the refining and petrochemical or ethanol industries. For years these gases were simply flared or vented, creating both pollution and CO_2 emissions, while the industries creating these waste gases were burning fossil fuels to produce the energy they needed, or importing electricity from the grid produced by fossil fuel power plants, creating yet more CO_2. By using these waste gases as a fuel, companies can reduce their energy costs as these gases are effectively free fuels, and contribute to global CO_2 reduction efforts.

Use of landfill gas as a fuel for power generation is one example of how an environmentally damaging waste gas has been used to generate power and reduce CO_2 emissions. Comprising predominantly methane and CO_2, landfill gas in many countries is flared, or in the worst case, vented since methane has a much higher global warming potential than CO_2 as shown in Table 1. However, with a little treatment, landfill gas can be used as a gas turbine fuel, even in DLE combustors. Thus a waste product can be utilised to create clean, efficient energy. In most cases landfill gas is used to generate only electricity, but there are some installations where landfill gas is the fuel for a cogeneration plant. Figure 6 shows a gas turbine installed on a University campus in the USA as part of a tri-generation plant, providing power all year round, heat in the winter and cooling in the summer.

While methane and CO_2 (or nitrogen) mixtures are relatively simple fuels to handle, even for DLE combustors, some of the process waste gases proposed as gas turbine fuels can be more challenging. One such challenge was in a Propane Dehydrogenation (PDH) plant in China, where the gas turbine driving one of the large process compressors was required to run on a highly variable process off-gas (Figure 7) while still achieving low NOx emissions.

Despite the variability of the fuel, composed mostly of ethane, propane and butane with occasionally small quantities

Figure 6 7MW class gas turbine installed in a tri-generation scheme in the USA

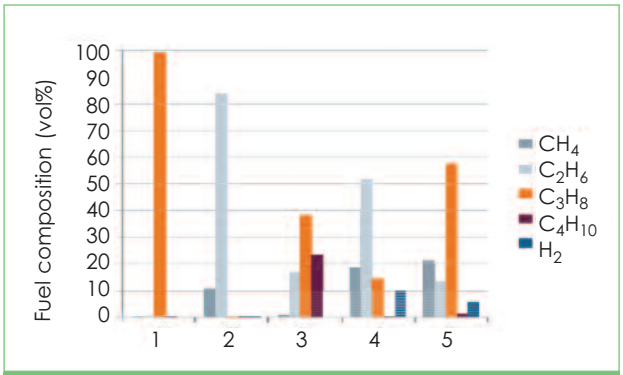

Figure 7 Snapshots of the differing fuel compositions seen by a 30MW class gas turbine in a PDH plant in China

of hydrogen being seen, the DLE combustion system has proven to be very robust and able to cope with the fuel variability without issue. The unit has now operated with excellent reliability for nearly 3 years. A second gas turbine has now been ordered by the same customer to operate on this process off-gas.

Some of the off gases can prove more challenging, and may not be suitable for use in DLE combustion systems. Refinery off-gas can have very high hydrogen contents, while Blast Furnace Gas (BFG) has a very low energy content requiring huge fuel volumes to be combusted. With fuel injector hole sizing issues and the high probability of flashback, it is more common to revert to diffusion flame combustion systems and alternate NOx abatement techniques if flaring of such gases is to be avoided.

Fuel gases from gasification and pyrolysis processes

Sometimes the proposed fuel, whether specifically identified as a fuel such as coal, biomass or a waste material, is solid in form and cannot be used directly in a gas turbine. Normally such fuels are combusted in boilers to drive steam turbines, but such plants tend to have quite low efficiencies creating comparatively high CO_2 emissions, especially if the fuel has high carbon content to start with.

These solid fuels can be combusted more efficiently by creating a syngas - a fuel gas created by using gasification or pyrolysis processes – and using it in a CCGT or gas turbine-

based cogeneration plant to obtain a higher efficiency and hence reduce CO_2 emissions. In some cases a 'double' GHG benefit can be gained as biomass and waste materials would otherwise be left to decompose, emitting CO_2 and methane into the atmosphere during this natural process. Gasification also potentially enables carbon removal from the fuel gas stream, creating a fuel that is basically 100% hydrogen and hence has zero CO_2 emissions, but this adds cost and a great deal of complexity into the process.

There are multiple different gasification processes available at various scales, creating a range of syngases with widely different compositions and energy contents. In general, the main combustible components in all syngas types are hydrogen and carbon monoxide (CO), with the rest of the syngas comprising inert gases and a small quantity of hydrocarbons. The energy content of these syngases typically ranges between 40% that of a similar volume of natural gas to as low as 10% that of natural gas. The low Wobbe Index and high hydrogen and carbon monoxide contents create multiple challenges for DLE combustors, so in most cases gas turbines would require to be fitted with diffusion flame combustion systems today.

Many projects have been proposed for gasification of coal, biomass or wastes but few have reached commercial operation due to cost overruns and technical challenges. However, it should be recognised that new and improved gasification technologies are emerging, and analysis indicates that syngas can be created at a competitive price compared to imported fuels such as LNG. With coal forecast to still be a major fuel source for years to come, the ability to use coal for power generation cleanly and with zero or reduced CO_2 emissions should not be ignored.

Hydrogen as a fuel gas

The presence of hydrogen in fuel gas streams has been mentioned in various sections above. With its fast flame speed it creates challenges for combustion engineers to maintain the flame in the correct place, especially when CO is also present in large quantities. Hydrogen's properties also create other engineering challenges that need to be addressed, such as hydrogen embrittlement and leakage, to ensure safe, reliable operation of the gas turbine. However, these challenges are well understood, and gas turbines have operated on hydrogen-rich fuels for many years, predominantly in refinery power generation and cogeneration applications.

Combusting hydrogen produces just water and no CO_2, although the high flame temperature creates high levels of NOx compared to natural gas. Thus hydrogen is an excellent fuel for a zero carbon power plant, but creates a challenge in maintaining NOx emissions within legislative limits which are usually based solely on what is achievable when operating on natural gas. With increasing intermittent renewable power generation from wind and solar, hydrogen is being examined as an energy storage medium: surplus renewable power would be used to electrolyze water to create hydrogen and oxygen. The hydrogen would be stored, either in tanks above ground or in underground caverns and depleted oil and gas fields, to be used as a gas turbine fuel when renewable power

Figure 8 7MW Class gas turbine installed in a refinery designed for operation on a high hydrogen off-gas. *Conoco, Humberside*

generation drops below the required level. In this way, the back-up power required to support intermittent renewable power generation on grid networks is also zero carbon.

Combusting 100% hydrogen is possible in diffusion flame combustors, but not today in a DLE combustor, although much work is ongoing to raise the acceptable hydrogen volume limits in the fuel. Most gas turbine OEMs today will quote maximum permissible hydrogen concentrations of 5% (vol) in the fuel for DLE combustors, although some models have been released for operation on higher levels, with up to 60% (vol) quoted when blended with natural gas, although a power derate may be applied to achieve this to mitigate the risk of flashback. Initial schemes using hydrogen-fuelled gas turbines to support renewables are therefore likely to be based on natural gas/hydrogen mixtures to ensure compliance with NOx emission legislation. While not zero carbon power generation, this does at least displace a potentially large volume of fossil fuel and generate CO_2 emission savings.

An alternate solution to the use of hydrogen in dedicated stand-alone power plants, based on the principle of partial displacement of fossil fuels, requires allowing an increase in hydrogen content in the natural gas pipeline network (such as shown in Figure 9). This would mean every natural gas-fired power generator set connected to the natural gas transmission system would combust a small percentage of hydrogen and reduce slightly its CO_2 emissions. However, it should be noted that every domestic and industrial appliance connected to the gas grid would also see this hydrogen content, so the maximum hydrogen content in the gas network would have to be set to minimise the cost of modifications to millions of gas-fired appliances. Gas pipeline operators also have concerns over the levels of hydrogen mixed with natural gas in the pipeline network, as a high partial pressure of hydrogen can promote stress corrosion and cracking. Calculations seem to indicate that on a pipeline network operating at 80 bar, 30% (vol) hydrogen is the maximum permissible, so it is likely that 15 to 20% (vol) will be the realistic maximum to allow for safety margins. Lower pressure pipelines can accept higher hydrogen concentrations, and so proposals such as Leeds H21

Figure 9 Energie Park Mainz, Germany: a Siemens Silyzer electrolysis system connected to a 10MW wind farm produces hydrogen for storage, injection into the natural gas grid and a trailer filling station

project, where the aim is to convert the whole city to hydrogen operation from natural gas, can potentially be achievable as the low pressure distribution systems also use polyethylene pipes which are well-suited for distributing hydrogen through the network.

Future possibilities for decarbonisation of power generation

The key methods discussed to date rely on improving energy efficiency, partially displacing fossil fuel or switching to lower carbon fuels to reduce the carbon footprint of power generation. Most development efforts remain in these areas, with hydrogen showing significant potential. Some research is also being undertaken on using ammonia produced using renewable energy and renewably generated hydrogen as a gas turbine fuel (Figure 10).

Another method of decreasing fossil fuel consumption is to use renewable/gas turbine hybrids, such as Integrated Solar Combined Cycle (ISCC). In these concepts, heat produced by the solar field is combined with heat recovered from the gas turbine to drive a steam turbine or Organic Rankine Cycle (ORC) turbo-generator. With such a configuration, the efficiency of a combined cycle plant can be boosted during daylight hours to over 70% from a typical 55% gas-fired only solution. Energy storage can be used to prolong the contribution of the solar field to the power plant output. Renewable energy is therefore used to partially displace fossil fuel consumption in the gas turbine, which in turn reduces CO_2 emissions.

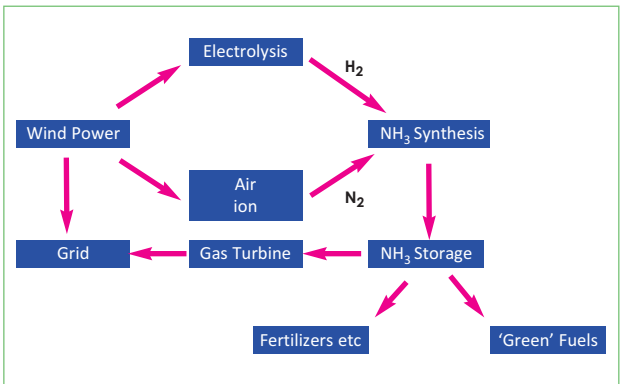

Figure 10 Simplified schematic of a 'green' ammonia synthesis and energy storage facility

As an alternative to using zero carbon fuels, much work has been undertaken on Carbon Capture and Storage (CCS). CCS would allow continued use of low cost, abundant fossil fuel resources, but has several drawbacks: it consumes a lot of energy, reducing power plant efficiency and increasing fuel consumption to produce the same power output, and it is a costly process both to capture the CO_2 and store it safely. CCS does not therefore lend itself to smaller scale power generation plants, or distributed power generation.

For smaller plants, carbon capture could be made economically viable by using the CO_2 captured to produce high value products, such as proteins or chemicals. Such concepts are being further investigated by many companies and the concept promoted by competitions such as the COSIA Carbon X-prize. Figure 12 shows how such a concept might work for an intermittently operated natural gas-fired gas turbine, combining carbon capture with renewably generated hydrogen to create a high value product. Such a concept can be employed on a small scale to create a fully sustainable mini-grid for islands or small communities, where waste products can be used to generate power which in turn provides the products required for agriculture or fish-farming with minimal overall CO_2 emissions.

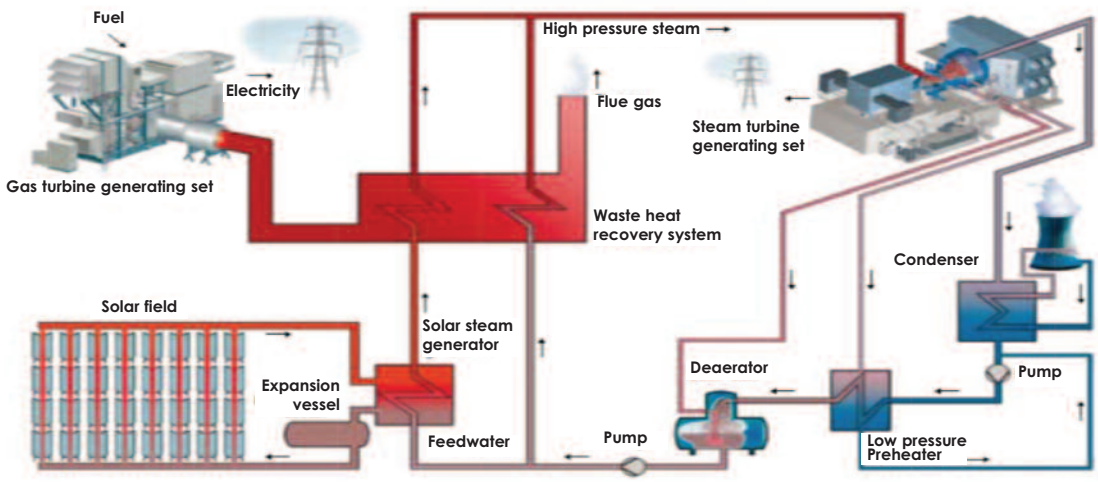

Figure 11 Typical schematic of an Integrated Solar Combined Cycle (ISCC) concept

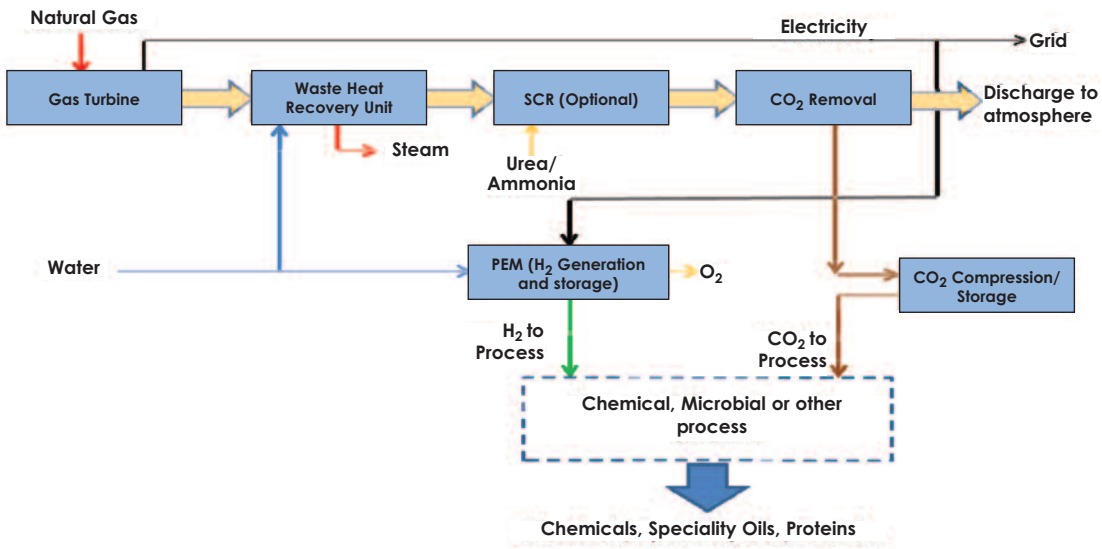

Figure 12 Concept 'Zero Carbon' intermittent power plant with chemical production from carbon capture

Conclusions

As demand for electricity continues to grow, unless action is taken the CO_2 emissions from power generation will also continue to rise. Various options exist to minimise this increase, or even potentially reduce CO_2 emissions while generating more power. The most appropriate option will depend on the scale of the power plant and the proposed fuel, but the fuel flexibility, and high combined cycle or cogeneration efficiency, of the industrial gas turbine indicate that gas turbines will have a major role to play in the power generation industry in creating clean, low or zero carbon electricity for many years to come.

Gas turbines are also well-positioned to become part of more complex sustainable hybrid power systems to provide not only power and heat, but also useful chemical products while at the same time minimising CO_2 emissions. ■

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Nomenclature

BFG	Blast Furnace Gas
Btu	British thermal unit
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COG	Coke Oven Gas
DLE	Dry Low Emissions
GHG	Greenhouse Gas
H_2	Hydrogen
HFO	Heavy Fuel Oil
ISCC	Integrated Solar Combined Cycle
LFO	Light Fuel Oil
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MWh	Megawatt Hour
NH_3	Ammonia
NOx	Oxides of Nitrogen
N_2O	Nitrous Oxide
ORC	Organic Rankine Cycle
PDH	Propane Dehydrogenation
SNG	Synthetic Natural Gas
UHC	Unburned Hydrocarbons

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The above paper was presented at the 9th International Gas Turbine Conference "The Role of the Gas Turbine in Today's Global Power Industry and other International Power Applications" in November 2017.

The bound book of conference papers is now available to buy from www.idgte.org £30 *(Students £15)*

Forthcoming events

The IDGTE hosts a wide range of social events, courses and conferences. All of our events focus on topical issues and developments within the energy industry and give an insight into the challenges facing the industry today.

Technology seminar and annual luncheon

Thursday 3 May 2018
Grange Tower Bridge Hotel

The 2018 IDGTE Technology Seminar and Luncheon is to be held once again at the Grange Tower Bridge Hotel. The day will commence at 10.00am with a morning seminar, followed by luncheon and guest speakers in the afternoon.

2017 event

The seminar will comprise a multi-stream programme covering a range of technologies and subject matter, so there will be something which is relevant to everyone's business.

The annual seminar and luncheon is well established as a key event in the calendar of the power and prime mover industries and is an occasion not to be missed.

This year's principal guest is Melle Kruisdijk - Vice President Europe, Wärtsilä.

Our guest speaker is Dave Coplin; author, alchemist, catalyst, Founder and CEO - The Envisioners, whose previous day job was Chief Envisioning Officer at Microsoft.

Tickets are on sale now at £150.

Concessionary ticket prices are available for IDGTE retired, student and young engineers.

Further information is available from our website www.idgte.org.

Papers day
October 2018

Following on from the successful papers days held previously at MAN Stockport, University of Lincoln and RWE Ferrybridge, plans are being finalised to hold a Gas Turbine Papers Day in October 2018.

If you are interested in presenting a technical paper at this event, please contact the IDGTE office.

Technical visits

Ricardo Technical Centre
May 2018

A visit is currently being planned in May to Ricardo's UK headquarters and Technical Centre at Shoreham.

Ricardo's Shoreham Technical Centre

We also plan to visit the research facilities of the CryoPower engine and systems at the University of Brighton.

CryoPower development rig at the University of Brighton

Wärtsila, Trieste
June 2018

In June 2018 a joint IDGTE/IMarEST technical visit to Wärtsila, Trieste, Italy is being planned.

Wärtsila, Trieste

Visitors will be able to follow the engine production lines, extending one kilometre through the heart of the factory, for a close-up view of the production process and the advanced technology and innovation that characterise the Group's operations in 70 countries.

The visit will be arranged near to a weekend so that people can extend their stay to visit Venice and the surrounding area.

If you are interested in any of these events please keep an eye on our website www.idgte.org for further details.

If your company or employer is able to host a visit to a manufacturing facility, launch of a new product or has a particular project that would be of interest to IDGTE members please contact us.

CHAIN 2018 Manchester

An Engineering Conference for Students and Young Engineers

What does the average student do on a cold, wet Saturday morning in February? Have a lie in and look forward to watching football on television or contemplate a trip to the pub later? Perhaps those made of sterner stuff are up and out, braving the elements on the football pitch – or whatever their sport happens to be.

> "What does the average student do on a cold, wet Saturday morning in February?"

Not the engineering students in Manchester and the North West though – it's 9.30am on 10th February and they are out in force, around 80 of them, gathering in the John Dalton Building of Manchester Metropolitan University eagerly awaiting the start of a full-day engineering conference – CHAIN 2018.

The CHAIN event, now in its third year, is the brainchild of Nick Valentine, a former student of Salford University. With a first-class honours degree in Mechanical Engineering and a distinction in his MSc in Robotics and Automation, Nick had the vision of creating a conference specifically for students and young engineers to encourage and broaden the horizons of those who have already chosen a career in engineering and to inspire those yet to decide on their future to consider engineering.

Attracting support and contributions from an impressive line-up of organisations including all the leading engineering institutions - Institution of Mechanical Engineers (IMechE), Institution of Engineering and Technology (IET), Institution of Civil Engineers (ICE), Institution of Structural Engineers (IStructE), Royal Aeronautical Society (RAeS), Nuclear Institute (NI) and, of course IDGTE, as well as Young Rail Professionals, European Young Engineers and the Manchester Association of Engineers, the CHAIN event can only be described as a huge success.

IDGTE again had a presence in the conference and with a stand in the exhibition area. Past President and Membership Committee Chairman, John Platt, presented IDGTE's contribution to the event. Congratulating those who had already chosen a great career in engineering, John spoke about "Engineering Challenge in Today's World". Referring to global statistics published recently by the Queen Elizabeth Prize for Engineering Foundation, which found that in a survey of public perceptions across 10 countries, 84% of people believed that engineering can make a difference to addressing major global challenges and 87% said they trust engineering businesses to make the world a better place, he cited the challenge, "The world is depending on you – are you up to the job?"

John went on to explain how IDGTE could help those whose interest and career path took them into the ever broadening area of power and prime mover technology, emphasising today's focus of the institution on renewable energy sources, alternative fuels and hybrid power systems. He encouraged any who were interested in joining IDGTE to contact us at our stand and said we would be particularly keen to speak to anyone who would like to be an IDGTE ambassador at their college or university.

John then invited Mark Cornforth to join him for an interview session. Mark is Technical Director of Maktec Marine Ltd and a recent new member of IDGTE. During the interview, Mark spoke about the involvement of his company with the "Team Britannia Around-the-World Challenge" – a quest to circumnavigate the globe in a power boat in record time, running on a hybrid emulsion diesel fuel. Illustrated by stunning photographs, the interview style approach was popular with the assembled company, clearly evidenced by the lively Q&A session afterwards, and many commented to us that it came as a refreshing change from the straight-forward Powerpoint presentations.

Mark Cornforth and John Platt at CHAIN 2018

You can read more about the "Team Britannia Around-the-World Challenge" and the involvement of Maktec Marine Ltd on pages 3 and 4 of this issue of the *Power Engineer*.

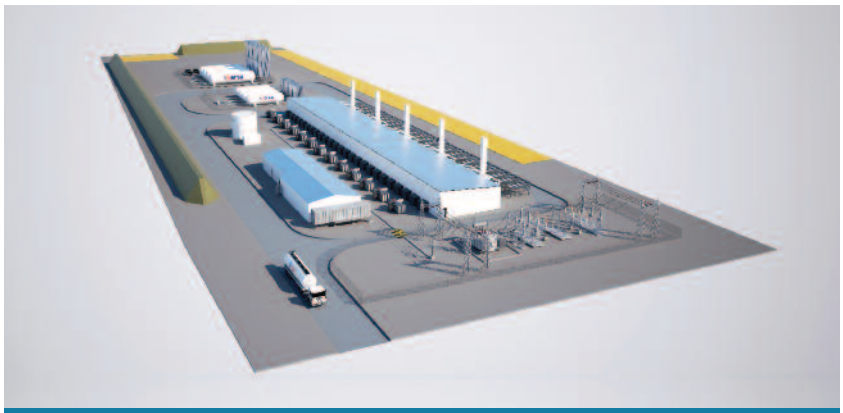
Our congratulations go to Nick Valentine and the team at CHAIN 2018 for an excellent event. We look forward to taking part on future occasions in Manchester and also the planned conferences to be held in Bristol and London. We wish them every success. ■

GASCO gets the go ahead for the first LPG based plant in Chile

GASCO, in partnership with INERSA, has announced the start of a project to build a power station 2km east of Teno city, in the Maule region of Chile. The complex of 45MW will contain 26 Caterpillar LPG gas engines.

The plant is designed to work completely with liquefied petroleum gas (LPG), and will inject electricity into Chile's central SIC grid, providing back-up capacity to compensate for the variability of output from power plants using wind or solar.

With an investment of USD 30 MM the power station will start operating by the end of 2018.



Artist's impression of the new 45MW power station in Chile

Marcelo Cortés Vásquez

From an engineering perspective this project has been lead by a multi-task engineering team with the participation of our IDGTE member - Marcelo Cortés Vásquez, GASCO GLP SA, Chile, who is taking the lead of all the LPG station design and construction. ■

idgtE welcomes new members

Professional Affiliate of the Engineering Council

Name	Company	Membership type
M Issa	Institut Maritime du Quebec	Student
D Corda	Cranfield University	Student
D A Pesola Ferreira	Cranfield University	Student
C Escott	Clarke Energy	Member

Restoring Sir Charles Parsons' final resting place

There is a current crowdfunding campaign to restore the final resting place of Sir Charles and Lady Katharine Parsons at Kirkwhelpington, Northumberland which Friends of the Discovery Museum, Newcastle think we should bring to your attention. Ruth Baldasera gives more information:

"Sir Charles and Lady Katharine Parsons passed away in the 1930s, and were buried in Kirkwhelpington. They had one son (Algernon) and one daughter (Rachel), but both children died unmarried and there were no grandchildren.

Parsons created Heaton Works in 1889, and the factory now owned by Siemens, still exists today, employing 600 people. At its peak there were over 12,000 personnel employed. Thousands of local people have benefited from employment at Parsons over the years, and hopefully the factory will go on to create jobs for many years to come. There are many places where you can read and learn about this extraordinary man, his achievements, his contribution to the North East and most people know of his record-breaking ship "Turbinia" which is at the Discovery Museum in Newcastle.

Sir Charles Parsons

Lady Parsons was a founding member of the Women's Engineering Society in 1919 (www.wes.org.uk) and served as the 2nd President of WES between 1922-1925, following her daughter, Rachel Parsons. Lady Parsons was an engineer of ability and had the distinction of being an Honorary Fellow of the North East Coast Institution of Engineers and Shipbuilders. At the time of her appointment she was the first lady to be elected an honorary fellow or honorary member of any British engineering society.

Major Algernon Parsons lost his life after 4 years service during WW1, and Rachel Parsons was a pioneering woman who took responsibility for training women for the Ministry of Munitions during WW1. (You can learn more about Rachel at https://parsonstown.info/people/rachel-parsons)

Their family home at Wylam was handed over as a military hospital, and the factory made over 8,000 searchlights during the Great War.

The stones need to be restored, and then I would like to leave the local parish a sum of money to look after the stones in the future."

For more information go to https://www.justgiving.com/crowdfunding/ruth-baldasera ■

Could you be an IDGTE ambassador?

IDGTE needs the help of its members, it is not onerous, it can fit in with your business/professional activity and could give you additional useful contacts. In this busy world we need to think innovatively about how we make contact with those companies and individuals who would benefit from involvement with IDGTE and vice versa. Therefore, IDGTE has set up an Ambassadors scheme that can lead the way for IDGTE's growth and development. Could you rise to such a challenge?

Being an Ambassador develops you as a person, extends your network and gives personal rewards. A dedicated area of IDGTE's web site provides an introduction to what being an Ambassador is all about and provides material for Ambassadors to use.

We are dedicated to developing the skills of our members in their specialist areas. Whether it is through sharing knowledge, bringing the right people together or providing practical advice, the IDGTE can help you get the most from your industry.

Professional Ambassadors

Professional Ambassadors are dedicated to the promotion and growth of IDGTE so as to better serve the members. Could you help by:

- securing new membership applications
- seeking out technical papers for presentation
- sourcing contributions for publication in *Power Engineer*

Partner Company Ambassadors

Partner Company Ambassadors foster the relationship between IDGTE and companies with emphasis on the promotion of IDGTE's Approved Company Scheme for registration of Engineering Technicians.

Interested contact - enquiries@idgte.org ■

Obituary

Dr Meherwan P Boyce

Meherwan Boyce

It is with great sadness we announce the death of Meherwan P Boyce on 21st December 2017 aged 75.

Professor Meherwan P Boyce, PhD, PE, CEng (UK), was the Chairman and CEO of The Boyce Consultancy Group, LLC and a Fellow of the following societies: American Society of Mechanical Engineers (ASME (USA)), Institution of Mechanical Engineers (IMechE (UK)), National Academy of Forensic Engineers (NAFE (USA)) and the Institution of Diesel and Gas Turbine Engineers (IDGTE (UK)).

His experience began in the field of turbomachinery in both industry and academia in 1962. Since 1998 he had been Chairman and CEO of The Boyce Consultancy Group, LLC. His past experience covered 20 years as Chairman and CEO of Boyce Engineering International Inc, founder of Cogen Technologies Inc, and five years as a designer of compressors and turbines for gas turbines of various gas turbine manufacturers.

His academic experience began in 1967 as an Instructor at the University of Oklahoma and included the position of Professor of Mechanical Engineering at Texas A&M University and founder of the Turbomachinery Laboratories and the Turbomachinery Symposium in 1972. He was the author of several books such as the *Gas Turbine Engineering Handbook* (Fourth Edition, Elsevier); *Cogeneration & Combined Cycle Power Plants* (Second Edition, ASME Press); and *Centrifugal Compressors, A Basic Guide* (PennWell Books). He was a contributor to several handbooks: his latest contributions were to the *Perry's Chemical Engineering Handbook* Seventh and Eight Editions (McGraw Hill) in the areas of Transport and Storage of Fluids and Gas Turbines. He has contributed chapters for the ASME's *Energy and Power Generation Handbook* and *A Handbook on Combined Cycle Systems for Near-Zero Emission Power Generation*.

He was Chair of the Committee which wrote the *ASME PTC 55 Gas Turbine Aircraft Engines*, which was approved as an American National Standard by the ANSI Board of Standards Review on 29th July 2013. He was also a member of the ASME Ethics Review Board. Additionally, Dr Boyce taught over 150 short courses around the world attended by over 3,000 students representing over 400 corporations.

Dr Boyce was the pioneer of On-Line Condition Based Performance Monitoring in 1978. He is also the recipient of two major patents: one in the area of surge control and the other in the area of external combustion firing in gas turbines. He developed models for various types of power plants and petrochemical complexes. His programs are being used around the world in power plants, offshore platforms and petrochemical complexes.

He was a consultant for major airlines in the area of engine selection, noise and emissions. His consultant expertise was utilised in the Aerospace, Petrochemical and Utility industries globally and was a much-requested speaker at universities and conferences throughout the world.

Dr Boyce has authored more than 150 technical papers and reports on gas turbines, compressors pumps, fluid mechanics, and turbomachinery.

Dr Boyce has been honoured by being appointed to membership of the following scholarly honorary societies such as Sigma Xi, Pi Tau Sigma, Phi Kappa Phi, and Tau Beta Phi. He is the recipient of the ASME Herb Allen award for Excellence in Aerodynamics and the Ralph Teetor Award of SAE for enhancement in Research and Teaching among others. His most recent award in 2016 was the Clifford C Furnas Memorial Award from The State University of New York at Buffalo.

Dr Boyce's involvement with our institution began when IDGTE gave CPD certification to his short courses held in London.

Meherwan became a Fellow of IDGTE in 1999 and presented at several IDGTE conferences and events.

Peter Tottman, Immediate Past President said:

"*Meherwan was a very significant contributor to the advancement of knowledge and exchange of information. He made that contribution with charm and grace. He was generous with his time and treated all those with whom he had contact with respect.*

His knowledge was rather special because it was very much the result of his personal diligent research and investigation."

To Meherwan's wife, Zarine, his son, Phiroz, and daughter, Anita, and all of you who knew Meherwan, we send our sincere condolences from our Trustees and Members. ■

A brief review of condition monitoring techniques for gas turbines

Dr Yu Zhang
Senior Lecturer, School of Engineering
University of Lincoln

Abstract

Gas turbines have played a key role in aeronautical industry, power generation and as mechanical drives for pumps and compressors. To monitor the efficiency and reliability of gas turbines, the employment and improvement of a remote condition monitoring and fault diagnostic system is of great importance. This paper introduces a scheme of condition monitoring for gas turbines, including sensor validation, steady-state and transient operation discrimination, and novelty or fault detection. Moreover, the methodologies are categorised as knowledge-based rules, signal processing-based techniques and model-based approaches. Among them, model-based approaches further take account of white-box, black-box and grey-box modelling techniques. The strengths and weaknesses of the methods are discussed, and future work in this research area is also recommended.

Keywords: Gas turbine; condition monitoring; fault diagnosis; signal processing; grey-box modelling.

1 Introduction

The development of Gas Turbines (GTs) started before World War II as a new trend for power generation. Nowadays, GTs have been utilised in many industrial sectors, including for power plants and offshore platforms [1]. Due to the complex and non-linear behaviours, GTs present some unknown and undesirable events occasionally, including unexpected shutdowns, over-heating, over-speed during GT operations and system disturbances due to fault or load fluctuations [2]. Consequently, the adoption of automatic condition monitoring and fault diagnostic systems, to identify anomalies and classify the emerging fault conditions, has attracted considerable attention due to widely recognised benefits of facilitating reduced down-time and assurance of safety [3].

The typical causes of GT performance deterioration include fouling, hot end damage, vibration, variable inlet guide vane and variable stator vane orientation or position problems, tip rubs and seal damage, foreign and domestic object damage, erosion, corrosion and control system malfunction, etc. [2] To monitor the engine performance deterioration, various sensors are strategically located throughout GTs to monitor the condition of systems or components, including compressor, combustor, turbine and other auxiliary items, at different positions in the GT engine. These sensors are used to measure the performance parameters of the GT, such as vibrations, pressures, temperatures, speeds and power outputs, so that the changes of any component characteristic can be identified by using the sensor measurements [4].

Following the stage of data collection, ie the sensor measurements, Section 2 introduces a scheme of condition monitoring for GTs, which are then categorised by the fault diagnostic methodologies, viz knowledge-based rules, signal processing-based approaches and model-based methods. In particular, signal processing and model-based methods are described in more detail in Sections 3 and 4 respectively. To conclude, Section 5 summarises the paper, and future work in this topic is also discussed towards the end.

2 Condition monitoring of gas turbines

The philosophy of condition monitoring for GTs usually involves the following main process steps:

(1) data collection and pre-processing;
(2) sensor validation, including signal reconstruction in the case of sensor fault;
(3) steady-state and transient operation ion;
(4) novelty detection and fault diagnostics in different operational regimes; and
(5) decision-making and fault report.

The key focus point is the fault diagnostic system, where there are many novelty/fault detection strategies, including trend and noise analysis on a single sensor [5] or on a group of sensors [6], and benchmarking or fingerprinting of steady-state [7], start-up [8] and shut-down operations [9] on the GTs.

Sensor validation and signal reconstruction

Sensors are taking the role of localised 'eyes and ears' on GTs. Sensor validation has the main purpose to assure that these sensors are functional and accurate, in order to prevent unnecessary shutdowns and maintenance, which would result in down-time and loss of productivity [10]. Typical types of sensor faults include empty readings, logged or constant readings and infrequent spike readings, which can be detected by setting simple rules in the diagnostic system. More subtle sensor faults can be detected via techniques, such as Principal Component Analysis (PCA) [11] and Self-Organising Map Neural Network (SOMNN) based techniques [12]. Although it is helpful to understand the performance of the sensors, eg precision and sensitivity,

via sensor tests, before they are installed on the GTs, it is not essential.

Following the identification of a faulty sensor, the faulty signal can be reconstructed to a 'best estimate', with a view to retaining the ability to keep the unit operational. Signal reconstruction can be achieved either by using the sensor measurements from a correlated sensor group, eg by extensions of PCA or SOMNN-based approaches [10], or by using an established GT model [13]. For instance, Figure 1 shows an example of faulted thermocouple measurement reconstruction, which is accomplished by an extended SOMNN algorithm based on the measurements from other correlated sensors in the sensor group. The results have shown that from the start of the fault period, the reconstructed signal follows the 'normal trend', as expected from the other sensors, reliably [10].

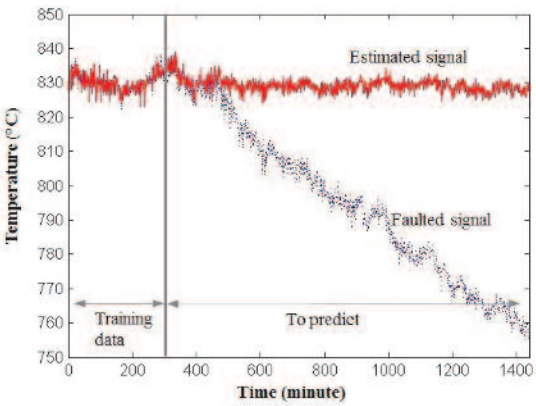


Figure 1 Reconstruction of faulted thermocouple signal using extended SOMNN [10]

Steady-state and transient operation ion

After sensor validation, the measurements are considered to be reliable for condition monitoring on machine components. A lot of traditional monitoring systems are based on algorithms that are only applicable during steady-state operating conditions, in which case, measurement transients caused by changes of loading or control actions can generate excessive 'false alarms'. Other techniques can only be applied under constrained regimes, eg during the engine start-up phase. Therefore, it is necessary to address the issue by incorporating implicit methods that discriminate between steady-state and transient behaviours as part of the fault diagnostic system. Noise extraction technique can be applied to monitor the step changes in the signal, in order to e steady-state and transient operations [14].

Alternatively, a Variational Bayesian Gaussian Mixture Model (VBGMM) method is used to facilitate the extraction of steady-state operations, by clustering its Gaussian mixture components automatically. For example, Figure 2 shows the result that VBGMM automatically clusters a set of vibration data to three mixture components. Since one component indicates a steady-state operation in this case, VBGMM can be used to distinguish transient operations from steady-state data, which then provides a convenient pre-processing tool for the subsequent novelty detection and fault diagnostic algorithms [15].

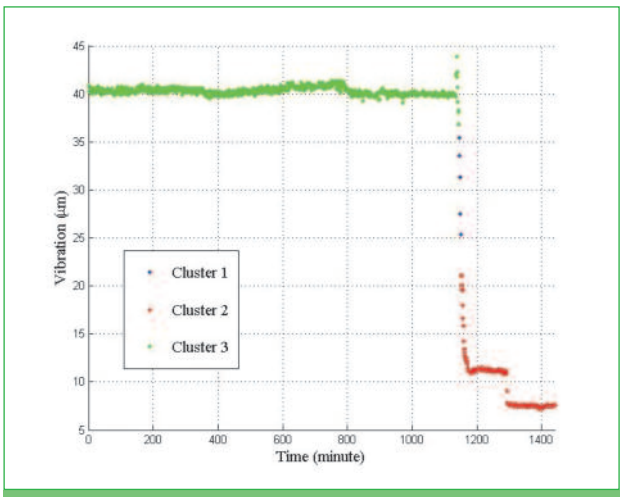


Figure 2 Automatic clustering of vibration signal by VBGMM [15]

Novelty and fault detection

Novelty detection and fault diagnostic techniques can be broadly classified into three categories, viz. knowledge-, signal processing-, and model-based approaches [5]. Knowledge-based rules are normally implemented by using the existing mechanism knowledge or empirical knowledge from the key experts, which depends on a long term accumulation of domain-specific industrial experiences. The fault diagnostic results are built on their related knowledge in the physical principles, fault mechanisms and relevant expertise of the GTs. The expert knowledge gives valuable insights into the GT system, but is always time consuming and labour intensive, and above all, subjective. With the increase of size and complexity of industrial processes, sole knowledge-based fault diagnosis can be often incomplete and lack of robustness to uncertain disturbances.

Nowadays, with fast development of sensor and computing technologies, more industrial diagnostic systems tend to use techniques based on direct signal processing, which provide for improved accuracy and the degree of automation and digitalisation. Existing signal processing-based techniques include statistical methods [16], Artificial Neural Networks (ANNs) [17] and other soft computing techniques [18]. On the other hand, model-based approaches have also gained favour, so as to provide virtual sensors by either a complete GT model [19] or individual GT component model [20]. A virtual sensor is used to provide an estimate of expected measurements, from which residuals are then used as an indicator of emerging or potential failure modes being present, which can be also used for reconstruction of sensor signals in the case of absent sensor or sensor failures.

Here, these latter two categories, ie signal processing and model-based approaches, will be explained in more detail in the next sections.

3 Signal processing-based approaches

Signal processing-based approaches do not rely on prior expert knowledge or the establishment of an accurate GT model, but depend on the precision and completeness of online and historical data collected on the GTs. Latent

features are then extracted from the sensor measurements, to characterise the health or fault conditions of the GT system. Signal processing techniques can be applied either to a single sensor, studying the statistical descriptions for the healthy and faulty conditions, or to a group of sensors, searching for the underlying relations among the correlated sensors.

Single sensor statistics-based methods

Zhang et al [3] have extended traditional Gaussian Mixture Model (GMM) techniques to detect emerging faults for industrial GT systems. A GMM with an Outlier Component (GMMOC) is defined and applied for the early detection of emerging faults. A primary advantage of the GMMOC method is its applicability for novelty detection when there is a lack of prior knowledge of fault patterns. An example is shown in Figure 3, where normal and abnormal data sets (in the form of features, ie mean and standard deviation, in this case) are correctly identified by using GMMOC [3].

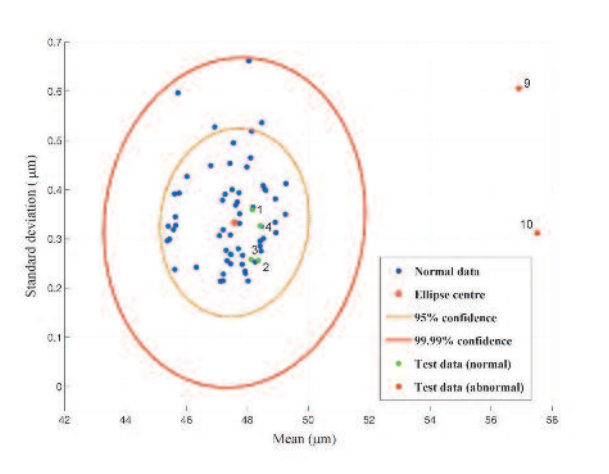


Figure 3 GMMOC for novelty detection [3]

Alternatively, Zhang et al [5] have integrated the use of empirical mode decomposition, PCA and Savitzky–Golay adaptive filtering, to extract noise from the underlying vibration and temperature measurements. Through analysis of the resulting noise, transient measurements associated with system load or demand changes can be effectively discriminated from those that are characteristic of emerging faults during steady-state operation. An example of the results by using the proposed techniques on bearing vibration data is shown in Figures 4 (a) and (b).

Both techniques are shown to be useful, however, to study and to set threshold for each single sensor individually makes this strategy less efficient, and difficult to be integrated in a systematic fault diagnostic structure for GTs, eg for those with more than a hundred sensors employed on an engine.

Sensor group correlation-based methods

Zhang et al [4] have presented approaches for novelty and fault detection based on measurements from multiple sensor groups, eg temperature and vibration sensors, for industrial GT systems. Specifically, the use of Hierarchical Clustering (HC) and SOMNNs are shown to provide robust and user-

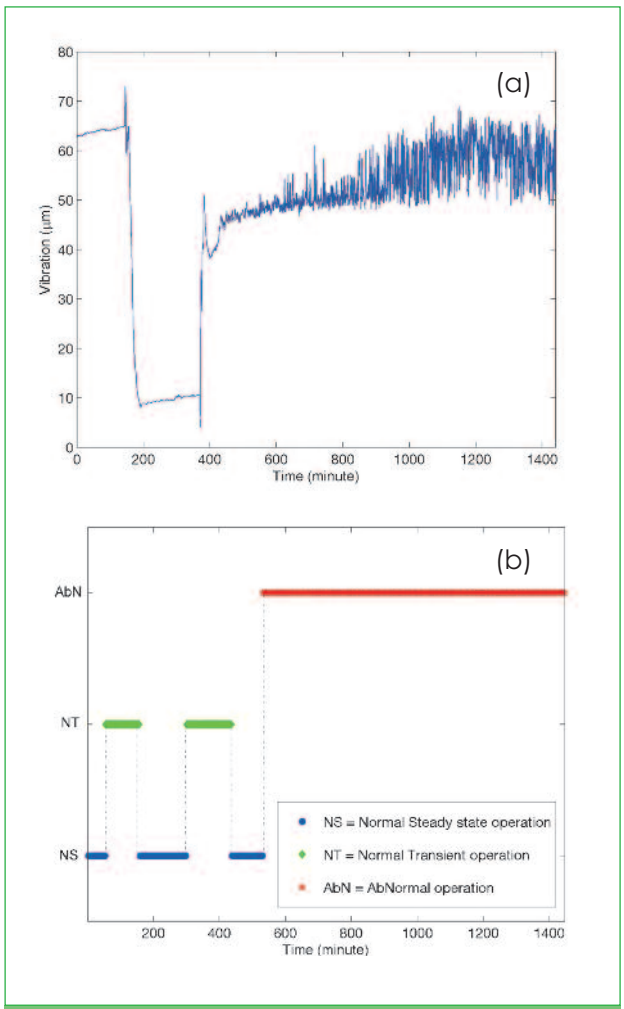


Figure 4 (a) Vibration measurements showing bearing faults (b) machine fault detection and normal transient operation ion [5]

friendly tools. HC fingerprints are found for normal operation, and fault detection is achieved by monitoring cluster changes occurring in the resulting dendrograms. Similarly, fingerprints of operational behaviour are also obtained using SOMNN based component maps that are initially determined during normal operation, and fault detection is performed by detecting changes in their self-organised maps. For instance, Figure 5(a) and (b) have both shown a change in characteristics of BTT6 (Burner Tip Temperature sensor #6), using HC dendrogram and SOMNN based component maps respectively, by comparing with the fingerprints of normal operational behaviours.

The proposed methods are shown to be capable of sensor and machine-fault detection and diagnosis from a large group of sensors that measure a variety of physical quantities. However, in order to build these fingerprints for GT normal operations, a significant amount of historical data is required. To overcome this constraint, Zhang et al [6] have introduced a simple scheme of an 'early warning' system for GTs, which attains low computational workload and less programming requirements, being therefore employable at an industrial level. The scheme includes trend analysis, which examines when the measurement shows different trends from the other measurements in the sensor group, and noise analysis, which examines when the measurement is displaying higher levels of

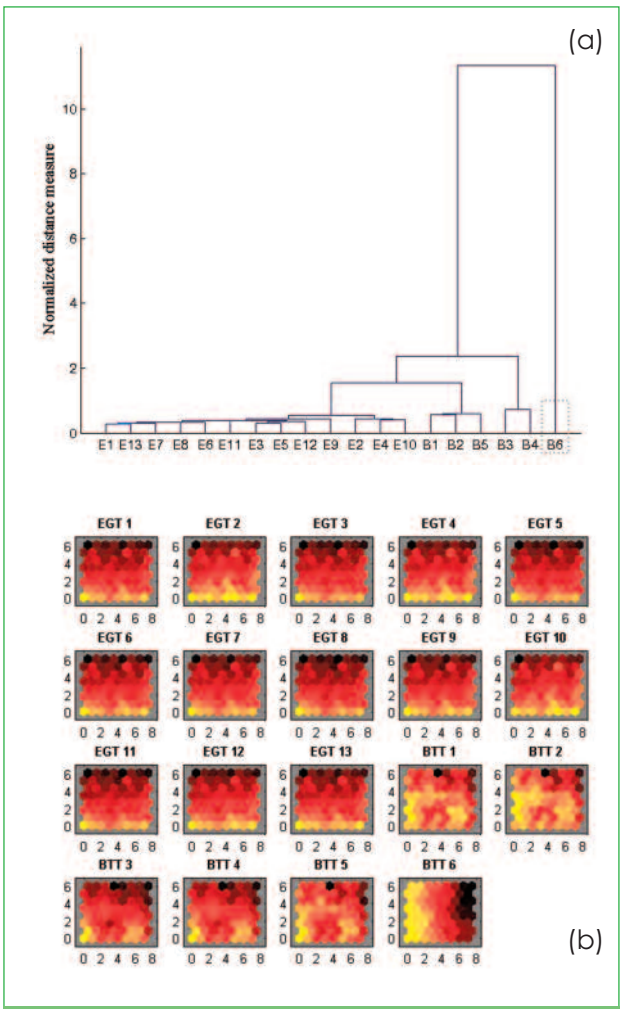


Figure 5 (a) HC dendrogram indicating BTT6 fault (E = EGT, B = BTT) (b) SOMNN component planes showing BTT6 fault (EGT = Exhaust Gas Temperature, BTT = Burner Tip Temperature) [4]

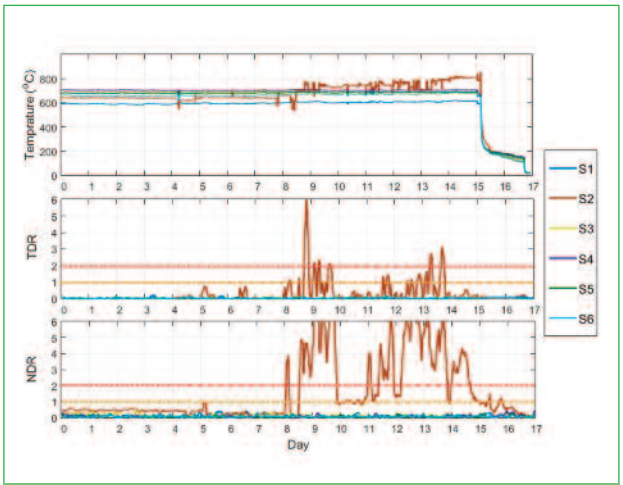


Figure 6 Case study on trend and noise analysis (S – Sensor, Orange threshold: Warning level, Red threshold: Fault level) [6]

noise compared to those of the other sensors. Figure 6 shows a case study on the introduced Trend Deviation Ratio (TDR) and Noise Deviation Ratio (NDR) indexes. The component fault measured by Sensor 2 is correctly identified by the TDR and NDR measures seven days before enforced engine shutdown [6].

The proposed method has not only overcome the constraint of the requirement for historical training data to build a 'benchmarking process' for normal operation, but also overcome the issue by accommodating transient (part-load) operational conditions of the unit, ie the sensor measurements varying with load conditions of the GTs, and provided a valuable alternative to the traditional techniques that can only provide reliable information during steady-state operation. However, the drawback of this method is that it is not applicable to an individual sensor if there are no other redundant or correlated sensors available, because the method is applied to a group of correlated sensors, measuring the deviation of one sensor readings from the prototypical behaviour of the group of sensors. For component condition monitoring, depending on an individual sensor, virtual sensor measurements based on GT models can be utilised.

4 Model-based approaches

"Essentially, all models are wrong, but some are useful. [21]"
No model is perfect because of the uncertainty and randomness of the real events. However, it is more valuable to find a sufficiently accurate and more generalised model, which is simple enough, computationally efficient and able to deal with environmental uncertainty. In the fault diagnostic context, these models, though imperfect, can lead to easier reasoning and finally the right decision-making. There are three categories in the modelling world, ie white-box, black-box and grey-box modelling.

White-box modelling

Designing a GT is aimed to obtain a high efficiency of the system. All calculations based on the design point usually use static models. However, transient operations must be considered to achieve the requested power. For instance, in a GT the highest temperature in the cycle is at the end of the combustion chamber, which is approximately the same as that at the inlet of the turbine. The maximum temperature that the turbine nozzles and blades (coated or otherwise) can withstand limits the turbine inlet temperature, relating to which, other parameters in the cycle, including maximum pressure ratio, are also limited. Increasing the turbine inlet temperature has been one of the main goals to improve the GT efficiency. The development of new materials, thermal barrier coatings and new cooling techniques has made it possible, although this has also resulted in more expensive components and the necessity of controlling these components to work in an adequate operating range. Finally, dynamic models of the GTs are needed, to evaluate the behaviour of the plant during different operation regimes with transients in order to keep the adequate operating range. These models are more complicated than the static models, where not only the combination of different components of the plant is simulated, and also the controllers to control and improve the efficiency of the whole turbine need to be considered.

Pure dynamic models of GTs are commonly difficult to achieve due to the complexity in the structure, the auxiliaries and the control system. Panov [13] has developed a Simulink model, which can be used to simulate start-up operation,

change of load, control system, power-system stabilities and real-time modelling of the industrial GTs. However, the modelled GT behaviours are very specific, and rely heavily on precise component maps delivered by explicit engine tests. One of the constraints is that the specifically pre-defined component maps are normally incomplete due to the restrictions of the testing facilities, environments and control limits, etc.

Black-box modelling

Black-box modelling is to learn the complex relationships between the inputs and outputs of the system, when no functional physical model exists. It did not attract much attention until ANN was invented, which possesses the ability to categorise non-linear and non-stationary behaviours based purely on input and output data, without any insight of the underlying system principles. ANN is a non-linear data modelling tool which was originally designed to mimic the neural structure of the human brain. ANNs work with neurons working information in parallel. The main structure of an artificial neuron consists mainly of three basic components: weight, bias and activation function. The total input for the neuron is passed on to a non-linear operator, known as activation function or transfer function, which performs a mathematical operation. ANNs are structured with learning algorithms, which are used to train the networks, so as to determine the unknown parameters. The architecture can be feed-forward networks, or feed-back (recurrent) networks. The feed-forward network travels only in one direction, whilst feed-back network can propagate signals into an earlier stage [22].

ANNs can be applied to solve a diverse quantity of tasks such as clustering, classification, regression and estimation problems, and their applications in industry is vast. For example, Iliyas et al [23] have used an ANN to generate 'soft sensors' for emission prediction based on the conventional process measurements, as an alternative to analogous hardware sensors, offering enhanced simplicity and reduced costs.

Recently, ANN applications are significantly rising due to the growth of powerful new development in big data and Deep Learning (DL) [24]. DL, as it sounds, aims to extract abstract features from a large amount of data, by using a series of neural networks and training the entire networks layer by layer. It has demonstrated great successes in artificial intelligence technologies, but has not yet been employed widely in industrial sectors for understandable reasons. DL requires a large amount of training data and also computational time. The same as other ANN models, despite their high learning ability, they depend greatly on the richness of the training data. Because they carry no physical insights of the studied system at all, lack ways of representations or logical inferences, they present high uncertainty when encountering new data which were not presented in the training data.

Grey-box modelling

White-box and black-box models both have their own strengths and weaknesses, nevertheless, they can be used to counter balance each other. White-box model is based purely on first principles, eg for a physical model using the Newtonian equations. These models can be over-complicated or impossible because of the amount of modelling needed for a full coverage of the structure and materials. So, a more practical approach is to start with measurements of the known data of the system, as mentioned though, with black-box modelling, there is no prior knowledge of the underlying physical meanings. Therefore, grey-box modelling is proposed as a combination of white-box and black-box models, where there is no complete physical model of the system, but based on some of the information of the system and some experimental data, the unknown parameters of the incomplete white-box model could be found using black-box techniques.

Zhang et al [25] have proposed a grey-box modelling methodology, which combines both rule based knowledge and black-box estimation. Specially, a refined Mamdani fuzzy system is proposed and adopted for system identification of a compressor on an industrial GT, and back-error-propagation algorithm is used to refine the fuzzy rules. This model is also used for prediction of compressor fouling. In a different aspect, Zhang et al [8] have applied an Adaptive Neuro-Fuzzy Inference System (ANFIS) to extract representative vibration signatures from healthy start-up vibration measurements, and then introduced similarity measures to identify novelty/fault situations for industrial GT condition monitoring during the start-up operations.

Furthermore, Zhang et al [26] have proposed a Bayesian Neuro-Fuzzy Modelling (BNFM) approach to estimate compressor discharge temperature (T2) measurements on an industrial GT at site, by using the test bed measurements of the engine. Figure 7(a) has shown the associated Gaussian Membership Functions (MFs) for the inputs: Speed (gas generator speed) and P2/P1 (P2 – compressor discharge

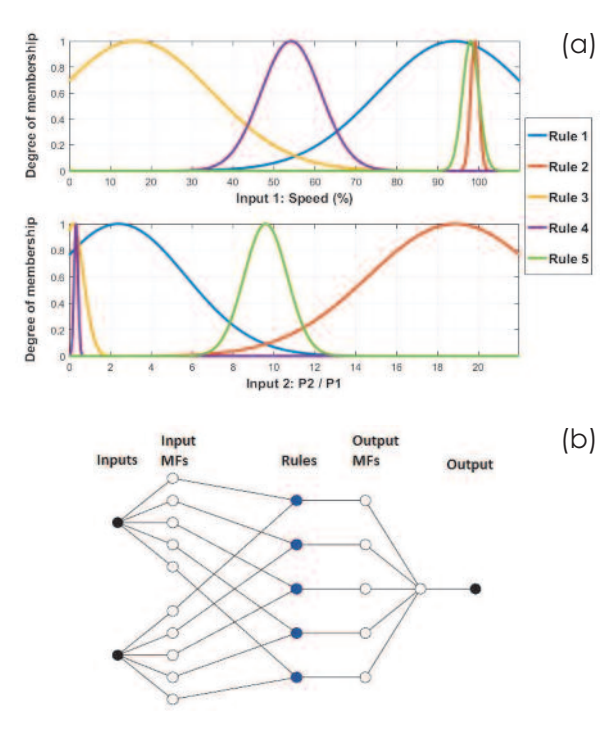


Figure 7 (a) Associated MFs of BNFM for Input 1: Speed (%) and Input 2: P2/P1 (pressure ratio); (b) BNFM structure for estimating the Output: T2/T1 (temperature ratio) [26]

pressure; P1 – ambient pressure). The corresponding fuzzy inference system structure is represented in Figure 7(b), where estimated T2 can be calculated from the BNFM output T2/T1 (T1 – ambient temperature). The modelling techniques are applicable for both missing sensor measurement estimation and condition monitoring of engine components.

There are vastly wide-ranging areas within grey-box modelling techniques to be explored, from a near-white-box model, eg by tuning some parameters within an existing white-box model using real measurements [19], to a near-black-box model, eg the ANFIS which uses neural networks to train a fuzzy system based on real GT input and output measurements [8].

5 Summary and future work

This paper has briefly summarised previous studies in the field of condition monitoring of industrial GTs. Firstly, it introduces the commonly encountered failure modes in GTs. Then, a scheme of condition monitoring for GTs is proposed, including data collection, sensor validation, steady-state and transient operation ion, novelty/fault detection and decision making. Furthermore, fault diagnostic techniques are categorised as knowledge, signal processing and model-based approaches. Among the signal processing-based and model-based methods, other than the white-box models, the rest of the methods are all fully or partially based on the real-world GT sensor measurements.

Within the reviewed signal processing-based techniques, the trend and noise analysis approach [6] has gained favour, which has been implemented to monitor a fleet of industrial GTs. It has shown robustness in accommodating changes of load and adaptiveness by not requiring historical data. Nevertheless, the main advantage is that it requires low computational workload and less programming demands, and therefore is preferred in an industrial environment. On the other hand, in the reviewed model-based techniques, grey-box modelling makes a priority choice in modelling GTs. Its flexibility can be presented by avoiding the complexity of the white-box models, while overcoming the intrinsic uncertainty of the black-box models. The semi-physical and semi-empirical models can interpret the relationship between system inputs and outputs, by carrying physical meanings, where the model parameters are determined by data-driven techniques with advantage of non-linear estimation [26].

Whereas the novelty and fault detection techniques are described in more detail in this paper, future work will focus more on the automation and integration of a condition monitoring and fault diagnostic system for GTs, where the starting stage, ie data collection and signal pre-processing, and the last stage, ie decision making and fault report, will be of great importance for the diagnostic system automation and integration.

Sensor fusion and integration

Due to the complexity of the GT system and uncertainty from the operating environment, there are normally multiple coupling factors for the fault occurrence, eg a downstream turbine blade damage as a result of a burner combustion failure. By analysing data from one single sensor, or from one single perspective, eg the correlated sensors, extracted fault information will always be limited. Therefore, sensor fusion and integration is a necessary next phase, to take into consideration heterogeneous data from different sources and in different aspects. For instance, temperature and pressure measurements can be fused to identify fault locations; or vibration signals can be complemented by acoustic signals [27] and thermal images [28] for diagnostic data mining.

Modelling/algorithm integration

So far, there is no existing single algorithm that can perform condition monitoring for GTs with full or high degree of confidence. However, every model/algorithm is designed for some specific applications, and therefore would bear an inevitable over-fitting problem. Moreover, each of the algorithms or models has its own strengths and weaknesses. For instance, a specific model/algorithm may exhibit a lack of adaptability and uncertainty tolerances, whilst a simplified model/algorithm will lose precision. Thus, there is a need for the integration of an automated decision-making platform for GTs using the information from all the available models and algorithms, to accommodate every aspect from common sense, extracted knowledge from data, reasoning mechanisms, dealing with uncertainty and imprecision, learning ability and adapting to a changing and unknown environment. ■

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About the author

Dr Yu Zhang is a Senior Lecturer in the School of Engineering, University of Lincoln. She has a broad engineering background, complemented with specific mathematical and computing skills.

Her current research interests focus on the development of data analysis techniques and novel modelling approaches, especially with efficacy in industrial applications, such as clustering analysis, artificial neural networks and grey-box modelling techniques.

Her future research will focus on Intelligent Industrial Systems and Advanced Materials Modelling.

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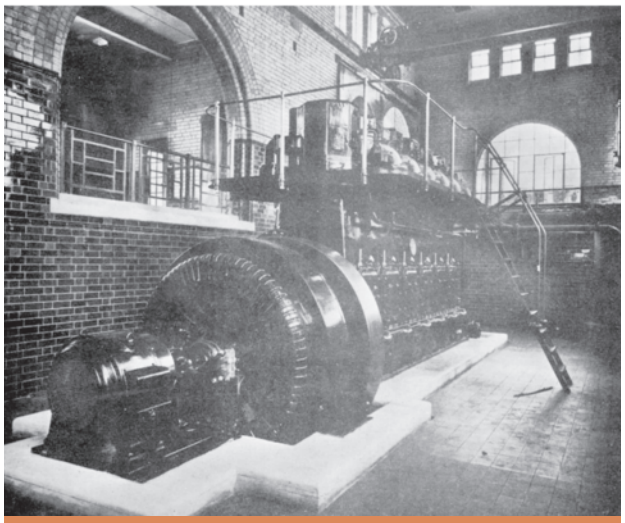
Our heritage

Report by Trevor Owen

Convertible engines

The Anson Engine Museum recently acquired a Ricardo test engine which is capable of being set up as either a spark ignition engine or as a compression ignition unit with a variable compression ratio. Ricardo undertook research into both fuel and engine performance from the earliest days using a series of engines which could accommodate a wide range of conditions. They acquired the engine which now resides at the museum to find the optimum performance settings for a particular fuel or engine design.



National Gas and Oil Engine BAC6 convertible 6-cylinder engine

A number of manufacturers produced such engines on a commercial basis, including Sissons and National Gas and Oil Engine Company, but this was a niche market sector with very small numbers being produced against specific orders. These orders typically came from research organisations or training establishments for use in laboratories.

The ability to convert standard production engines was also offered commercially by manufacturers at various times in the past where flexibility of operation was required. Sometimes this was to optimise operation where conditions could change either seasonally or by the availability of a different fuel source. On some occasions this was in anticipation of future developments in engine operation by manufacturers whilst providing a source of power in the interim period.

In the 1930s gas and diesel engine design was developing across a broad front and a number of manufacturers could supply a 'convertible' engine with additional parts to enable an engine to be reconfigured at site to change the mode of operation from gas to diesel and vice versa. This change entailed rebuilding the engine in situ and needed to be planned for periods when the engine output was not required. This concept became obsolete once dual fuel engine designs became established in the 1940s where engines could change over from one fuel source to another with the engine in operation by simply moving a lever.

National Gas and Oil Engine Company introduced a range of convertible engines based around their B series design in the 1930s and supplied a BAC (B = 16 inch bore x 21.5 inch stroke, A = vertical engine, C = convertible) 6-cylinder spark ignition engine to a local sewage works in Birmingham with the ability to be rebuilt at site as a diesel engine should the gas supply fail. This engine was used for very successful long-term trials on sewage gas and was subsequently converted to run as a dual fuel engine in 1939.

Many manufacturers produced dual fuel engines in the 1940s and 50s as it became an established design for reliable power typically for sewage works. In the 1960s the availability of natural gas increased substantially worldwide and the dual fuel engine market increased to meet the demand for generating power with such gas as the primary fuel. Around this time some manufacturers supplied engines with provision for later conversion to gas operation by bolting on the additional components for dual fuel gas operation. It would be difficult to machine the additional holes required for the dual fuel kit as substantial machining facilities would be required along with a major strip-down of the engine. Hence it was cost-effective to have the additional holes produced during the original manufacturing process if there was any chance of a conversion being required at a later date.

Mirrlees Blackstone supplied a number of their K Major engines with all the additional holes machined into the major parts from the outset to facilitate later conversion to dual fuel gas burning configuration. For example the KV16 Major sets supplied in the 1970s to a power station in Alice Springs Power were subsequently converted into dual fuel engines in the 1980s when natural gas became available locally.

You can still see conversions happening in current times associated with the transfer and reinstallation of existing land-based engines for a new application. There are also some new engine applications where a different fuel supply will be available at some future date or where new regulations are pending, both requiring an upgrade to the engine specification. This can also happen in marine applications where a vessel is sold or moved to a different route and the fuel and emission requirements are reviewed leading to an update of the engine build.

Midsummer Mingle diesel reunion event
Anson Engine Museum

The date for the next event is Wednesday 27th June 2018. Further details will be announced in due course.

Future heritage papers

We are still looking for Members to either write a heritage article or provide suitable material on engines or manufacturers which have not yet been covered since the series commenced in 2005.

Any feedback or memories on relevant subjects would be welcome. Anyone with suitable material or memories should contact the Bedford Office in the first instance.

DEUA/IDGTE on-line library of heritage papers of engines and manufacturers

The Members' Area of the website provides access to past DEUA and IDGTE papers. There is a comprehensive library of more recent papers and then a more limited availability going back in time. A full list of the papers published by the DEUA and IDGTE from 1916 to 2017 is available in pdf format for viewing at www.idgte.org/Papers1913-2017.pdf.

The Anson Engine Museum

Poynton, Cheshire, SK12 1TD

2018 Programme

The Museum season commences at Easter and continues until the 'Turn the Clocks Back' weekend in October. Certain days are allocated for operating the steam engine collection in addition to the other engines. The dates for special event days are as follows:

1/2 April	Easter Opening
6/7 May	Live steam days with craft fair
16 June	1000 Engine Rally special opening from 1600 to 2100
17 June	Fathers' Day Event
23/24 June	Gardner 150th Anniversary Celebrations
27 June	Midsummer Mingle
22 July	Live steam day with craft fair
26/27 August	Live steam days with craft fair
23 September	Live steam day with craft fair
27/28 October	'Turn the clocks back' closing weekend event

Full details of the opening times and special event details can be found on the museum website at www.enginemuseum.org

Gardner 150th Anniversary 22-24 June 2018

This year will see the celebration of 150 years since Lawrence Gardner went into business in Manchester as a machinist and went on to form L Gardner and Sons Ltd as a limited company in 1903.

The museum has specialised in Gardner engines from the outset and now has a considerable collection covering a wide range of production types and dates. The collection has been extended over the past year to include some further examples ready for the anniversary year.

The Gardner engine was the preferred choice for many bus and truck operators in the period from the 1940s to the 1980s and many engines were sold on for further use (often overseas) when the original vehicle was scrapped. The key advantages of the Gardner engine were reliability combined with a low fuel consumption compared with other designs on the market in the UK.

The engine manufacturer at one stage rationed engine deliveries to its customers but later supply problems with strikes forced many customers to use alternative suppliers. The takeover of the company by Hawker Siddeley Group and then Perkins led to the company ceasing production in the 1990s. The introduction of new regulations on emissions meant that the existing engine design could not be modified to meet the requirements and a totally new design was required. Such is the reputation of the Gardner engine that one can still purchase 'as new' remanufactured engines from specialist suppliers.

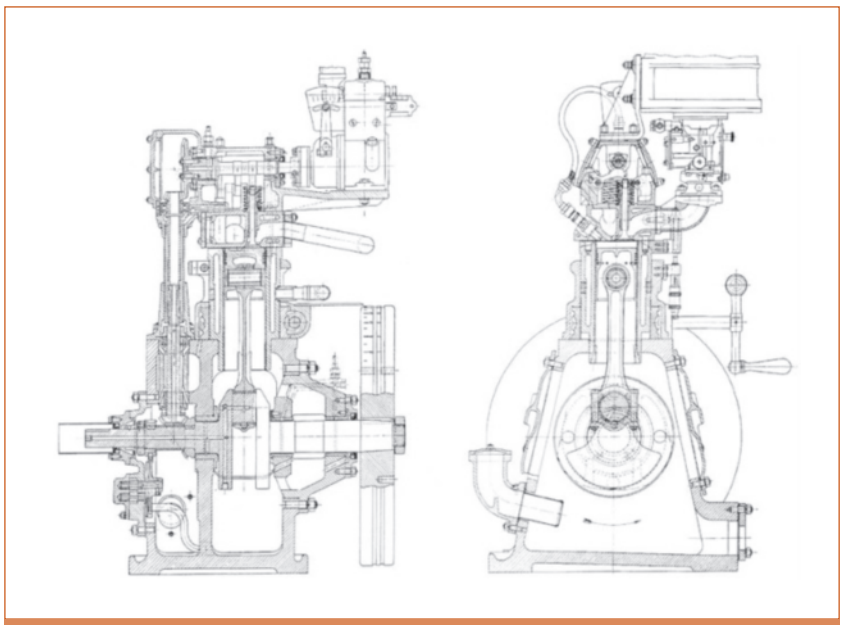
The museum was fortunate to acquire a horizontal 6 HLW cylinder version as used in many single decker bus applications and this will be on display for the celebrations.

Horizontal Gardner 6HLW former bus engine being unloaded at the museum

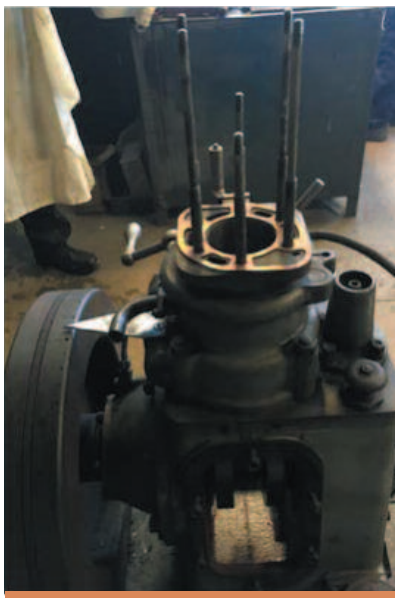
Ricardo test engine

The museum has recently acquired a Ricardo test engine which is now on display in a newly created area of the museum.

The Ricardo E6 variable compression test engine was developed for research into engine performance under varying compression ratios with different fuels. It is a naturally aspirated four stroke water cooled engine of 3 inch bore and 4.375 inch stroke with a capacity of 507cc. It can operate at compression ratios of 4:1 to 22:1 with liquid or gaseous fuels and can operate in various modes including spark ignition or compression ignition by changing the engine build. A supercharged configuration was also available. The engine was rated at 12bhp as a spark-ignition unit and 11bhp as a compression ignition unit, both at 3,000rpm. The engine operates on the wet sump logic where oil is circulated to a tank with a pumped



Sectional drawings of the Ricardo test engine



Ricardo test engine in the museum workshop

return from the sump to the tank. Various devices are fitted to enable measurements and samples to be taken as typical with any development engine.

Promotional video

A promotional video has been uploaded to YouTube and can be viewed at www.youtube.com/watch?v=TUKfJ_YOUcg; this gives a good over-view of what is available to view at the museum for those who haven't visited previously.

Engine dating enquiries

The museum can provide a dating record service for Crossley, Tangye, Mirrlees, Blackstone and Gardner engines. It is acknowledged that the records are not fully complete but the staff will use their best endeavours to provide a relevant response. To use this facility a form needs to be downloaded from the museum website and completed.

Internal Fire Museum of Power

Tanygroes, Cardiganshire, Wales, SA43 2JS

Opening times

The museum is open from Easter until early October. See more at www.internalfire.com.

Steam Hall

Work has continued over the winter period in completing and populating the new steam hall. This will further extend the tour of the museum to include the steam engine collection in addition to the diesel and gas turbine exhibits.

Latest news

The museum has now provided a link to their news section on Facebook which can be accessed without a Facebook Account or sign-in being required. The link is https://www.facebook.com/pages/Internal-Fire-Museum-Of-Power/198568506925586

eBay shop

The Museum operates an eBay shop which offers a range of publications such as operational manuals and books recording the history of various engines plus some parts for the renovation of smaller engines. There is a link to the relevant webpage from the museum website at www.internalfire.com

View of the new steam hall during the engine installation stage

Reference library

The museum offers a considerable volume of reference material on a wide range of engines and other machinery with full access being made available to those who register with the museum website. The content includes brochures and manuals for Lister, Petter and W H Allen products.

See www.internalfire.com for more information. ■

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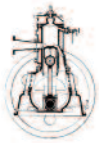
ANSON ENGINE MUSEUM



Internal Fire
Museum of Power

MLA Accredited Museum

Internal Fire covers the history of the internal combustion engine with an emphasis on larger diesel engines and gas turbines. The museum operates the oldest daily running Diesel engine in the world as well as the only remaining Proteus gas turbine driven "Pocket Power Station".

The museum operates engines on a daily basis, for opening times see the website below.

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[1]Total cost of ownership is defined by Shell Lubricants as the total amount spent on industrial equipment, including the cost of acquisition and operation over its entire working life and the cost of lost production during equipment downtime.