



Renewable Power Generation using Turbo-expander at Blue-NG Pressure Reduction Station

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1 Introduction

Blue-NG is planning to install a combined cycle bio-generator (CCBG) plant at its Beckton gas pressure reduction station (PRS). This will be a combined heat and power (CHP) plant fuelled by bio-fuel only and the electricity generated is likely to qualify as being generated from an eligible renewable source under the Renewables Obligation (RO).

The plant will consist of a diesel engine generating unit in which bio-fuel (ie bio-diesel) will be burnt to generate electricity with a thermal efficiency of around 47% (ie the fraction of the input thermal energy of the fuel converted into electricity) based on the gross calorific value of the bio-fuel. As a result, over 50% of the heat energy released from the bio-fuel will remain partly in the exhaust gas of the engine and partly in the cooling water that will be circulated through the engine to keep its temperature at an acceptable level. Blue-NG is considering recovering the heat from both engine the exhaust gas and the cooling water in order to use it to generate additional power in two other systems, as described below, with a view to improve the thermal efficiency of the CCBG plant.

- The first of these will be an Organic Rankine Cycle (ORC) system. This system will use a working fluid (a mixture of hydrocarbons) which will first be pressurised in a compressor and then heated by engine exhaust gas/cooling water in a heat exchanger. This hot pressurised fluid will then be expanded in a turbine-generator system to generate electricity. Both the pressure and the temperature of the working fluid will decrease due to this expansion. The working fluid will then be cooled further in a heat exchanger by transferring the residual heat to natural gas at high pressure flowing through the pipeline system operated by Nation Grid Gas (NGG) plc. The heated natural gas will be used in a second system as described below. The cooled working fluid will then be compressed, heated and expanded to repeat the cycle. The compressor will be powered with either electricity from the generator or electricity from grid which will be metered.
- The second system will use a turbo-expander to generate electricity by using natural at high pressure flowing through the NGG pipeline system after being heated initially by the working fluid in the ORC system and then by residual heat available from engine exhaust gas/cooling water. Both the pressure and the temperature of the natural gas will decrease due to expansion in the turbo-expander.

2 Pressure Reduction Station

Straight Pressure Reduction by Throttle Valve

Natural gas is transmitted through long distance pipe lines under high pressure. However, this pressure is not suitable for local gas distribution networks supplying customers for use in domestic and industrial gas appliances. Usually, a pressure reduction valve (PRV) ie a throttle valve (also known as Joule-Thompson valve) is used at a PRS to reduce natural gas pressure before supply to local gas distribution network. This pressure reduction in a PRS by a throttle valve results in reduction of both pressure and temperature of natural gas. For example, natural gas throttled from 25barg and 10°C to 3barg would be cooled by about 6.5°C ie will be at about 3.5°C after pressure reduction. It is a normal practice to have provision for heating natural gas at PRS, preferably before throttling, so that its temperature is maintained at an acceptable level after throttling to avoid operational and material integrity problems in local gas distribution network that can be caused by low gas temperature. It is estimated that 22kJ of heat would be required per kg of natural gas to preheat it to 16.5°C before throttling which will leave the gas at 3barg and 10°C after throttling. It should be noted that heat supply to a heat exchanger would be higher than 22kJ per kg of natural gas (eg about 28kg/jkJ), as in practice around 80% of heat supplied will be transferred to natural gas.

There will be no change in enthalpy (ie total energy) of the gas before and after throttling ie this is an isenthalpic process. The enthalpy of a gas is a thermodynamic property and is defined as:

$$h = E + pV$$

where,

h is the enthalpy,

E is the internal energy of gas which depends on its temperature,

p is the pressure of gas,

V is the volume of gas, and

pV (the product of pressure and volume) is usually termed as flow work,

Although the total energy (ie enthalpy) of gas does not decrease by throttling, it is degraded ie reaches a lower level and hence there is reduced scope of extracting useful work from it. From thermodynamic consideration, a heat engine extracts heat from a heat source at higher temperature using a working fluid, converts a part of this heat into useful work (eg mechanical work, generating electricity etc) and rejects the rest of heat to a heat sink at a lower temperature. The efficiency of a heat engine depends on the temperatures of the heat source and the heat sink, and increases with the increase in difference of these two temperatures.

It should be noted that although a vast amount of energy is contained in sea water at ambient temperature, useful work cannot be extracted from it as no sink is readily available at a lower temperature to reject heat.

Turbo-expander

Instead of throttling, natural gas supplied to a PRS at high pressure can be expanded directly in a turbo-expander to generate electricity before onward supply to local gas distribution network. Both the pressure and the temperature of natural gas will decrease with this expansion process and heating of gas will be necessary to raise its temperature before supply to local gas network for avoiding operational and material integrity problems. Blue-NG is not considering this option at its Beckton PRS. Instead, they are considering heating high pressure natural gas (supplied at 25barg and 10°C to PRS) to a higher temperature by extracting waste heat from the bio-fuel engine, then expanding this gas in a turbo-expander to generate electricity. They have argued that this turbo-expander will produce electricity entirely from the waste heat extracted from renewable energy and thus will be eligible under the RO as renewable generation.

For a turbo-expander with an isentropic efficiency of around 75%, the natural gas would have to be heated to around 115°C at 25 barg before expansion in order to achieve 3 barg and 10°C after expansion. This would require 255 kJ of heat per kg of gas which would be recovered from the waste heat of the bio-fuel generating unit. The estimated electricity generation in the turbo-expander would be 0.055 kWh/kg of gas (198 kJ of heat per kg of gas being converted to electricity), after allowing 15% mechanical and generation losses. As a result, the electricity generated in the turbo-expander will come entirely from the waste heat from the bio-fuel engine.

However, if sufficient heat is not available from the bio-fuel engine for any reason to heat natural gas to a high enough temperature, the expansion in the turbo-expander may result in a fall in gas temperature below that at which waste heat was added prior to expansion. If the gas temperature after expansion in the turbo-expander falls below the temperature prior to its heating, the electricity generated in the turbo-expander will come not only from the heat supplied to natural gas by bio-fuel engine but also from energy already contained in the natural gas before heating from the bio-fuel ie heat which was not supplied by the bio-fuel. This can be explained as follows.

For a gas the equation of state is defined as

$$pV=nRT$$

where

p is its pressure

V is the volume

n is the number of moles of gas

T is its temperature

R is the gas constant

Both the pressure and the temperature of natural gas will decrease, and its volume will increase as results of expansion in the turbo-expander to generate electricity. The Equation of State of the gas at different stages is:

before heating by bio-fuel : $P_0V_0 = nRT_0$;

after heating by bio-fuel : $P_1V_1 = nRT_1$;

after expansion in the turbo-expander : $P_2V_2 = nRT_2$.

Enthalpy (total energy) of the gas before heating: $h_0 = U_0 + P_0V_0$;

Enthalpy after heating : $h_1 = U_1 + P_1V_1$;

Enthalpy after expansion $h_2 = U_2 + P_2V_2$;

The enthalpy will decrease during expansion through the turbo-expander which will be used in generating electricity. As a result, h_2 will always be less than h_1 . However, h_2 could be less than or higher than h_0 depending on whether T_2 is less than or higher than T_0 .

If the temperature of the gas after expansion (ie T_2) is higher than that before heating by bio-fuel (ie T_0), then $P_2V_2 (=nRT_2)$ will be higher than $P_0V_0 (=nRT_0)$ and the energy contained in the gas before heating will not contribute to the electricity generated at all and all of it will come entirely from the energy added by bio-fuel heating. On the other hand, if the T_2 is less than T_0 , then $P_2V_2 (=nRT_2)$ will be less than $P_0V_0 (=nRT_0)$ and the generation will come not only from the heat added from bio-fuel heating but also from the energy contained in the gas before heating.

Hence, to ensure that the electricity generated in the turbo-expander comes entirely from the waste heat of the bio-fuel engine, the temperature of natural gas after expansion (T_2) must be equal to or above the temperature prior to its heating by the bio-fuel waste heat before expansion (T_0).

It is, therefore, essential to continuously monitor the temperature of gas at a point just before waste heat is added to it and also at a point just after its expansion in the turbo-expander to check that the electricity generated is entirely from bio-fuel waste heat. Otherwise, energy contained in the gas before addition of waste heat will contribute to electricity generated and will not entirely come from waste heat.

Effect of Temperature on Turbo-expander Generation

The temperature to which gas is heated before entering the turbo-expander will affect the amount of electricity generation. For example if the gas at 25barg and 10°C is heated to 87°C by the bio-fuel engine waste heat and expanded to 3barg in the turbo-expander its temperature would fall to -10°C . It would require 182kJ of heat per kg of gas to heat it from 10°C to 87°C at 25barg. The expansion of this gas to 3barg and -10°C in the turbo-expander would generate 0.049kWh of electricity per kg (using 176kJ of heat per kg of gas). As the temperature of natural gas after expansion (ie -10°C) fell below the temperature at which waste heat was added to it (ie 10°C), electricity generated in the turbo-expander came partially from the waste heat and partly from the energy contained in the natural gas before addition of waste heat prior to expansion. If this situation occurred in a given month then the station would not be eligible for ROCs in that month.

Effect of mass flow rate on Turbo-expander Generation

The total amount of electricity generated in the turbo-expander will be affected by the mass flow rate of natural gas through it. If the mass flow rate of gas is reduced the amount of electricity generated will decrease provided all other operating parameters (eg pressure, temperature) remain the same.

Effect of natural gas pressure on Turbo-expander Generation

A reduction of natural gas pressure through the turbo-expander will not contribute to electricity generation provided its temperature after expansion remains equal to or above that before heating by waste heat prior to expansion. However, a change in gas pressure at turbo-expander inlet may affect the mass flow rate of gas and hence electricity production. Fluctuations in gas pressure at turbo-expander inlet may also adversely affect the operation of the turbo-expander.

3 Conclusions

Blue-NG proposed turbo-expander can generate electricity entirely from waste heat of bio-fuel engine provided the temperature of the natural gas after expansion remains at or above that before waste heat addition prior to expansion.

There is a need to monitor the temperatures of natural gas before heat addition and after expansion to ensure that only waste heat supplied is used to generate electricity and energy contained in the gas prior to heating does not contribute to this generation in a given month.

Variation in mass flow rate of gas will affect the amount of electricity generated.

Fluctuations in gas pressure entering the turbo-expander will have an affect on the mass flow rate and may also adversely affect the operation of it.

Reduction in natural gas pressure in the turbo-expander will not contribute to electricity generation if its temperature after expansion is maintained at or above the level before waste heat addition prior to expansion.

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