Programme Area: Carbon Capture and Storage

Project: High Hydrogen

Title: Basis of Design Document for HSL WP2 Task 3 HRSG Test Rig for ETI

Abstract:

This document provides the rationale for the design and manufacture of the test rig forming Work Package 2 Task 2.3. This document is one of two for the HRSG experiments and provides the details of the test rig, what parameters it has been designed for to support the test program.

Context:

Hydrogen is likely to be an increasingly important fuel component in the future. This £3.5m project was designed to advance the safe design and operation of gas turbines, reciprocating engines and combined heat and power systems using hydrogen-based fuels. Through new modelling and large-scale experimental work the project sought to identify the bounds of safe design and operation of high efficiency combined cycle gas turbine and combined heat and power systems operating on a range of fuels with high and variable concentrations of hydrogen. The goal of the project was to increase the range of fuels that can be safely used in power and heat generating plant. The project involved the Health and Safety Laboratory, an agency of the Health and Safety Executive, in collaboration with Imperial Consultants, the consulting arm of Imperial College London.

Basis of Design Document for HSL WP2 Task 3 HRSG Test Rig for ETI

20th November 2014.
Version V0.10

An agency of the Health and Safety Executive

ISO 9001 Approved

ISO 14001 Approved

Investor In People

Version Control

Version	By	Comments	Release Date
V 0.01	Keith Moodie	*Initial Draft Release*	*27/03/2014*
V 0.02	*Keith Moodie*	*Amended Draft Release*	*25/04/2014*
V 0.03	*Keith Moodie*	*Updated Draft Release*	*8/07/2014*
V 0.04	*Keith Moodie*	*Updated Draft Release*	*24/07/2014*
V 0.05	*Keith Moodie*	*Updated draft Release*	*06/08/2014*
V 0.06	*John Gummer*	*Updated draft Release*	*06/08/2014*
V 0.07	*Keith Moodie*	*Updated draft Release*	*05/09/2014*
V 0.09	*Keith Moodie*	*Updated draft Release*	*11/11/2014*
V 0.10	*Keith Moodie*	*Final Version Release*	*20/11/2014*

SUMMARY

This document describes the design parameters for the second test rig to be constructed on the HSL Buxton site in order to complete the contracted work that HSL and ICL have undertaken to deliver under a consortium agreement with ETI. The project is being delivered in three phases. Phase 1 was a literature review of current knowledge for the use of hydrogen and hydrogen blended fuels in the current electrical generation sectors, and concentrated on gas engines (turbine and reciprocating) utilising heat recovery steam generating (HRSG) boilers attached to their exhaust systems. There was also a series of laboratory experiments to determine, the turbulent flame velocities, pressure rises from ignition, and auto-ignition temperatures etc.

Phase two followed the first phase, for which HSL constructed and operated a 12m long by 0.6m dia. duct, utilising a gas turbine to provide the mass flow and temperature conditions within this duct. Experiments were undertaken to determine the resultant pressure rises, flame speeds and temperature rises across various H_2, H_2/CH_4 and H_2/CO mixtures with varying equivalence ratios in the duct, both with and without a tube bundle that provided a blockage of approximately 40%. These experiments have provided guidance on the fuel mixes and equivalence ratios that could support an estimated maximum pressure rise of no more than 1 barg. The rig operated with flow temperatures of 400-600°C; however, in the experiments the lagged wall temperatures never rose above 300°C.

Phase 3 of the project requires HSL to build an approximately 1/8th scale model of a (HRSG) section as utilised by GE on its 350 MWe CCGT systems. The model will be attached to the end of the existing Phase 2 test rig and therefore uses the same turbine, fuel injection and ignition source. The HRSG will have similar temperature and velocity profiles up to the heat exchanger tube bundle as expected in the full size unit. The velocity profile will remain similar throughout the model up to the exhaust stack. However the temperature profile will differ after the tube bundles as there is no heat recovery to reduce the temperature. The region after the tube bundle will be longer than scaling requires in order to support monitoring of the pressure and flame front in this area.

CFD simulations of the flow through the model have been performed to provide evidence that the velocity profiles will be similar to those in the full size units. The CFD will also be utilised to determine the time needed to reach steady state conditions throughout the test rig following injection of the fuel test mixtures and prior to initiating the ignition in the circular duct. This will ensure consistency of start conditions for the data measured. Due to the size and operating conditions of the test rig the mixed fuel flow rates will be greater and may need a longer time to reach equilibrium, consequently additional storage capacity will be required for the mixed gasses and oxygen being used in the test programme. The heat exchanger tube section of the HRSG will provide between 5 and 15 rows in blocks of five rows.

The Phase 3 HRSG will be designed to comply with the following general guidelines:-

1. Maximum static pressure rise 5 barg
2. Operating temperature 400-600°C
3. A maximum wall temperature of 300°C

4. An HRSG that physically resembles a typical GE 350 MWe CCGT design.
5. A velocity profile to match a standard HRSG, 60-90m/s at entry, 6-7m/s uniformly after the tube bundle.
6. The tube bundle size will be industrial standard 38mm tubes with fins attached to provide a 70mm outside diameter, with a 40% blockage ratio
7. The tube layout will be to industry standards.
8. The existing Phase 2 test rig will, with some minor modifications, provide the required gas temperatures, mass flow rates, mixed fuel addition, ignition device, controls and data logging systems for the Phase 3 test rig.
9. The engine exhaust mass flow in the duct will be no more than 11 kg/s over the operating temperature range.
10. The mass flows for the injected fuel mixtures, including the make-up oxygen, will be in the range 0.038 – 2.0 kg/s.

Table of Contents

1 Introduction

This document provides the rationale for the design and manufacture of the test rig forming Work Package 2 Task 3 (WP 2.3) as required under the terms and conditions of the ETI Contract Number PE02162. Section 6, Task 3: Experimental investigation using a scale model of typical combined cycle gas turbine (engine) (CCGT(E)) and heat recovery steam generator (HRSG) systems. The rig's installation, commissioning and operating procedures will be covered in separate documents.

The basis of the rig's design is the provision of a scale model of an actual turbine exhaust system and HRSG, the latter containing a heat exchanger (HE). As such the resulting experimental facility can be used to investigate the flame out of CCGT/CCGE systems and the consequences of unburnt fuel passing through the turbine (in the CCGT case) and into the exhaust system.

In such circumstances the maximum hydrogen concentration in the downstream mixture is not expected to exceed 10-12% v/v hydrogen (when fuelled with pure hydrogen). The gas will be at temperatures of the order of 400–600^{0}C, depending on the turbine exhaust composition and the degree of compression achieved in the compressor. For CCGE applications the hydrogen concentration may be higher by up to a factor of two.

If re-ignition in the exhaust system is then assumed to occur, this sub-task of the project seeks to assess the potential consequences, particularly with reference to the flame acceleration, overpressure generation and possibly even detonation propensity of the air/fuel mixtures as they pass through the exhaust duct, the expansion section and finally the heat recovery system including the heat exchanger.

1.1 Objectives

The specific objectives of this part of the overall programme of work (WP 2.3) are primarily to investigate the influence of the HRSG situated in the exhaust flow of a CCGT or CCGE on the flame development and overpressure generation of representative gas mixtures when ignited immediately downstream of the turbine outlet. The tests will therefore build on the data from the 600 mm duct experiments of WP 2.2, by introducing key elements of the HRSG geometry for the selected systems of high-hydrogen fuels already investigated in WP 2.2.

The main focus of the tests will be around the impact of the HE tube bundle contained within the HRSG, which will contain up to 15 rows of tubes, these are made up in bundles of 5 rows. The particular focus will be the flame acceleration and overpressures that are likely to be generated inside and at the end of the HE as a function of fuel composition, equivalence ratio and flame velocity at the entry in to it.

As part of this, the test programme will seek to establish where for the given spacing between the tubes of the heat exchanger the major/critical acceleration of a propagating flame takes place, and the number of rows beyond which no further effects are seen. As such any appropriate scaling criteria can also be identified and predictions made of the hazards at full scale.

From this, the WP 2.3 test programme will also seek to specify the critical operating conditions in terms of flame velocity, flame acceleration and overpressures generated that can be utilised to increase confidence in the operation of existing systems and can also be related to reactivity parameters based on the results of WP 2.1 studies. In electing fuel mixes for the WP 2.3 test programme the results from WP 2.2 will provide guidance, also on how to avoid unacceptably high overpressures. The WP 2.3 facility is scaled and instrumented to be able to recognise detonation propensity and even DDT when it unfortunately happens, but not to retain such conditions as the aim is to determine upper limits to safe operating conditions with overpressures in the range 1-2 bar.

1.2 Meeting the objectives

The objectives of the project will be met by designing and manufacturing a test rig that is representative of the chosen GE HRSG design, then commissioning it and undertaking a series of measurements using this test rig as outlined in Section 3. The test rig will then be used to complete the agreed test matrix, which will be confirmed prior to the test programme commencing. The test programme will investigate the effect of flame acceleration on pressure rise, in order to investigate the risk of excessive overpressures and the onset of detonation for the fuel systems selected.

The test rig will be an approximately 1/8th scale model of an existing GE designed CCGT system. The rationale for using this size of rig is based on 1) a compromise between interest in achieving sufficient scale to mimic industrial facilities whilst accommodating (unintended) DDT of highly diluted fuel mixtures, 2) to use as part of the system the WP 2.1 rig with realistic gas velocities across the expanding transition duct, and 3) to limit costs without affecting their relevance. Consistent experimental and theoretical evidence shows that fuel mixture compositions with marginal detonation behaviour have detonation cell sizes which are characteristically several times that of a stoichiometric fuel mixture and rises asymptotically towards the detonation limit within a few per cent for further mixture dilution. Detonation cell widths for stoichiometric hydrogen-air are approximately 10 mm at near ambient conditions, with a critical channel width for detonation propagation of no more than this. For 100% methane-air mixtures cell width can be between one to two factors higher. At the proposed scale it will be feasible to accommodate spatially DDT propensity close to high-hydrogen detonation composition limits, accommodating multiple detonation cells within the entry and exit sections of the heat exchanger assembly with constant overall cross sectional dimensions. Within the former, DDT propensity may be unlikely, but to date we only have evidence from low gas velocities in the Task 2 constant cross area duct, while in Task 3 we will be dealing with a high entry velocity and potentially a more turbulent environment in the expanding duct section. The consequences from any DDT within the HE tube array can readily be accommodated in the latter section outlet area.

The fifteen tube HE array is not scaled as it utilises standard HE tube arrangements and sizes. Within the tube array near-stoichiometry cell sizes could nominally be accommodated within the spacing between the HE tubes. However, it is not appropriate to consider established detonation cell structures of DDT within such a highly turbulent and extremely hot environment with very high local sonic velocities, which is best considered as a highly violent and very hot explosion which may initiate proper detonation behaviour upon exit from the tube constrained confinement.

The experimental programme will test and build on the findings from WP 1, WP 2.1 and WP 2.2, using a hot vitiated gas flow at several but constant turbine exhaust flow rates. These will enable validation to be controlled in a systematic manner for the modelling, test results and the scaling parameters obtained from WP 2.2. The facility may also provide a better appreciation of the technology required to control and operate safely gas turbine engines running with hydrogen-enriched fuels safely. In particular this will apply to where and when a combustible gas mixture may exist in the exhaust gas stream immediately downstream of the turbine.

2 Rationale behind the design approach to the rig

2.1 Basis of the proposal

The basis of the proposal is a reduced scale model of an actual CCGT, being loosely based on the GE 350 MW unit shown in Figure 1 below. The rig will be used to gather relevant information relating to the behaviour of flowing flammable gas mixtures once ignited and passing through a model heat exchanger. The reduced scale for the rig is approximately 1/8th based initially on the respective power outputs of the GE unit and that of the R-R Viper gas turbine also used in the WP 2.2 test programme.

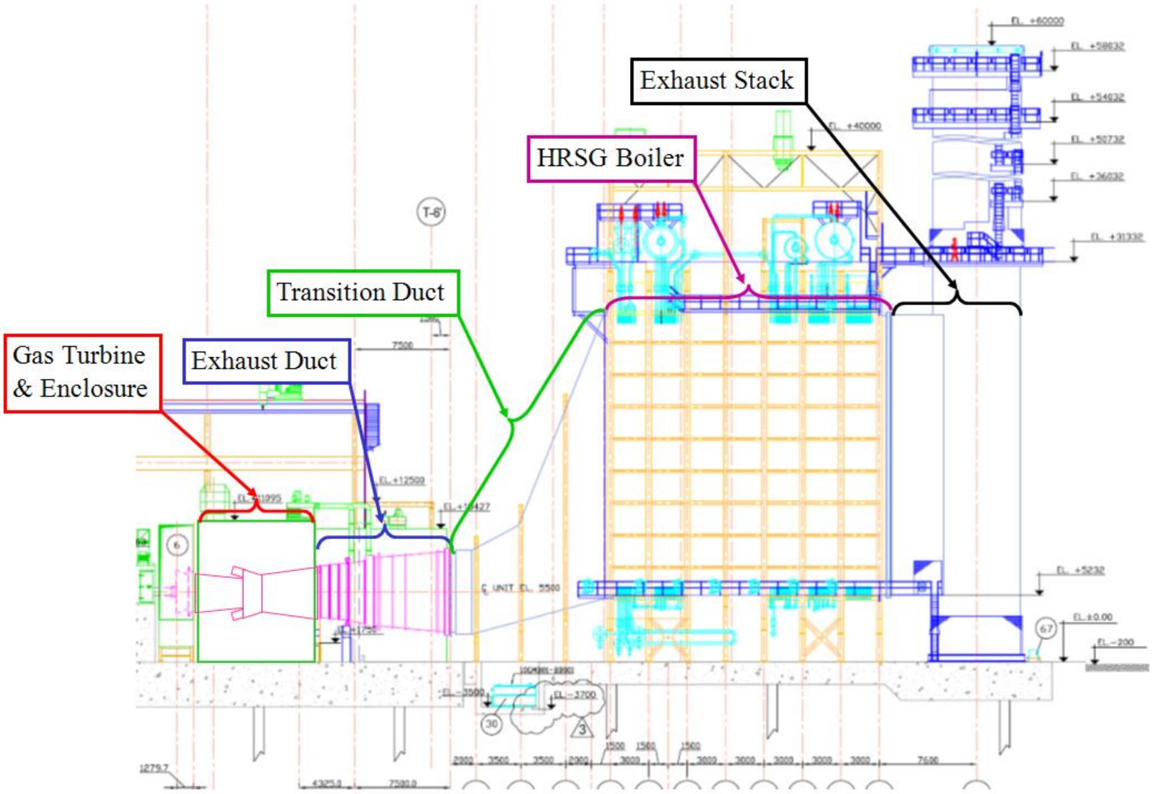


Figure 1:- GE 350 MW CCGT.

The important parameters to be preserved and the deviations from the scaling process are as follows:-

- The gas velocities in the model are to be kept the same in the model as in the full scale unit (NB: These velocities are obtained from the cross sectional areas of the various components of the full size unit, the exhaust gas temperature and its known mass flow rate).
- The aspect ratio to be used for the height/width of the model heat exchanger will be the same as at full scale; namely 2:1.

- The heat exchanger tube size with finning, but with a 40% blockage ratio will be the same as at full scale, in this case 38 mm tube outside diameter.
- The scaled distance from the beginning of the HE tube bundle to the end of the HRSG will be extended beyond the actual scaled distance to allow space for measuring the properties of the flame fronts and pressure waves emerging from the tube bundle (scaled length of 3.95 m extended to 6.35 m).
- A single tube bank only will be used. This will consist of up to fifteen rows of tubes, made up of three banks of five tube rows per bank.
- The tube bank will be situated at the upstream end of the HRSG.
- Temperature and velocity distributions to be used on entry into the model heat exchanger will be similar to those of the full scale GE unit and similar units (Maximum HE inlet velocities are around 25-30 m/s and peak towards the central region of the inlet plane).
- The heat exchanger design will be such that within the first 2-3 rows of tubes the velocity distribution will have equalised across the section to a value, just after the exit from the tube bank , of around 6-7 m/s.

NB: The nomenclature used in Figure 1 to identify the various components of the CCGT has been utilised throughout the following sections of the document.

A typical velocity contour distribution across the vertical central plane from the start of the transition duct of a CCGT to the first row of the heat exchanger tubes in shown at the right hand end of Figure 2 below (Courtesy of D. Abbott). This is a 2-D simulation typifying the flow patterns found in such systems. It is shown for illustrative purposes only and has not been used to provide definitive velocity contours. An in-house 3-D CFD simulation has been undertaken of the proposed model CCGT to show the velocity distribution expected for the proposed model.

In a typical design there may be several tube banks and these may also be placed vertically rather than horizontally. The GE based CCGT design modelled for this exercise is one with the tube banks running horizontally, and only the first tube bank is modelled. In the task 3 design the tubes themselves run vertically.

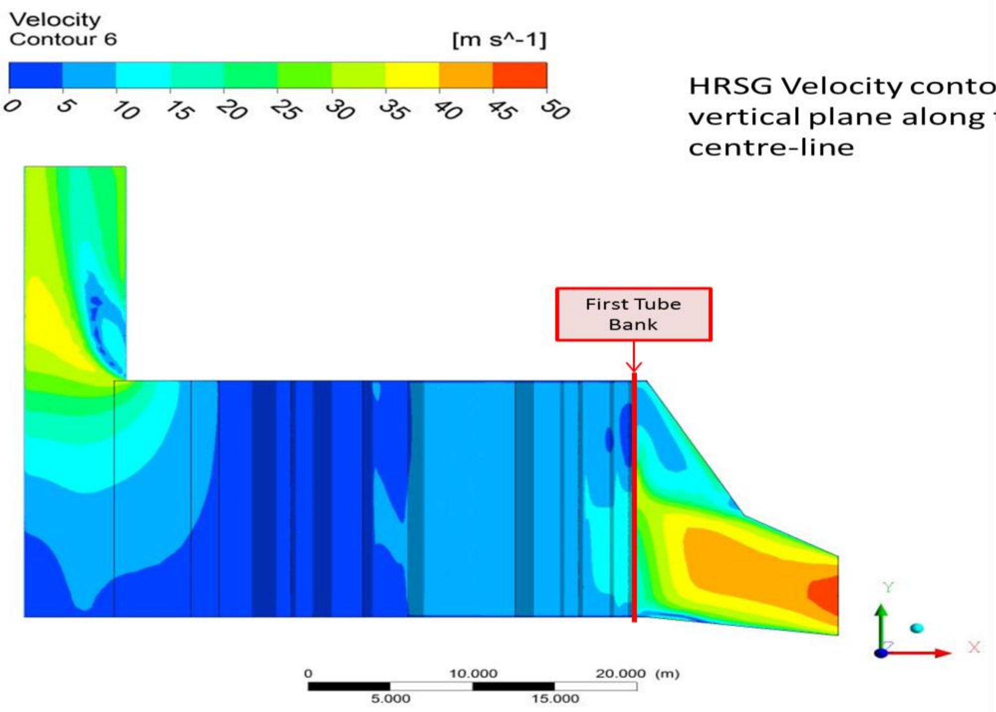


Figure 2:- Velocity distribution through typical heat exchanger [Courtesy of D. Abbott**].**

It is also recognised that current CCGT/CCGE designs are not capable of withstanding overpressures from strong explosions or detonations, and the advised limit is an overpressure of 1 bar. However, as it is necessary to extend the test boundaries beyond the current limits in order to establish as clearly as possible from over- and under pressure results the highest fuel concentration limits that can be withstood. The consortium have therefore sought to provide a rig in which the test boundaries (avoiding detonations) can be extended whilst still maintaining the integrity of the structure. The critical issue is how to conceive a design that despite the restrictions will enable the consortia to capture most of the relevant phenomena including pressure data up to the point of impact with the HE exhaust section end wall, and that will also provide sufficient information to model the total behaviour expected when there is present a full HRSG enclosure with a stack.

2.1.1 CFD simulations of the flow through the rig

A 3-D CFD simulation of the flow through the proposed scale model HRSG has been undertaken at HSL. Its purpose being to demonstrate that the flow patterns obtained within the transition section immediately upstream of the heat exchanger tube bank, are similar to those reported for full scale HRSG systems, in particular the GE system being scaled.

Gas velocities through typical commercial HRSG installations can vary over a wide range, with turbine exit velocities being in the range of 60-90 m/s. In the GE case this velocity is 85 m/s, which gives a velocity at the start of the transition duct of 55 m/s. When expanded out through the heat exchanger tube bundle this equates to typical uniform velocities of 6-7 m/s downstream. However typical inlet velocity profiles into the first row of heat exchanger tubes are not uniform, varying from almost zero up to 25-30 m/s in the central region of the entry plane.

The methodology and the results from the CFD simulations are shown in Appendix 1. The CFD model geometry of the CCGT and tube bundle was constructed using the dimensions given in Figure 4, which is a scaled version of the actual GE unit. The simulations were performed using a CFD geometry in which the tube bundle was represented by a distributed-porosity model with a fixed pressure drop across the simulated tube bundle. The pressure drop through the tube bundle was assumed to be 20-30 mbar in order to ensure that the CFD model correctly accounted for the flow resistance through the actual tube matrix. This pressure drop was taken from the information provided by GE in respect of the HRSG being modelled that is shown in Figure 1.

Initially steady-state CFD simulations were performed to examine the flow behaviour for a fixed inlet temperature of 550°C. The turbine exit velocity (600 mm duct exit) was fixed at 85 m/s and the flow was modelled as turbine exhaust gases (with no additional fuel present). The exhaust stack opening was sized to give exhaust stack velocities (40-45 m/s), which are typical of actual the GE unit and other CCGT systems. The model used an inlet turbulence intensity of 13%, which was the value measured for a turbine exit velocity of 85 m/s in the commissioning trials for the WP 2.2 test rig. An assumed turbulence length scale was also used. The walls of the duct were assumed to be at a fixed temperature of 300°C. A “fine” grid was used to try to minimise grid-sensitivity effects. The choice of the turbulence model was based on information from the literature.

The velocity contours along the central plane of the HRSG with an open top are shown in Figure 3, as predicted by the CFD simulation. This may be compared with similar predictions for this type of HRSG design.

See Appendix 1 for a more detailed assessment. The simulations have also looked at the grid sensitivity, the effects of grid porosity, the effects of the outlet design, and the time varying concentrations when hydrogen gas is added into the exhaust composition.

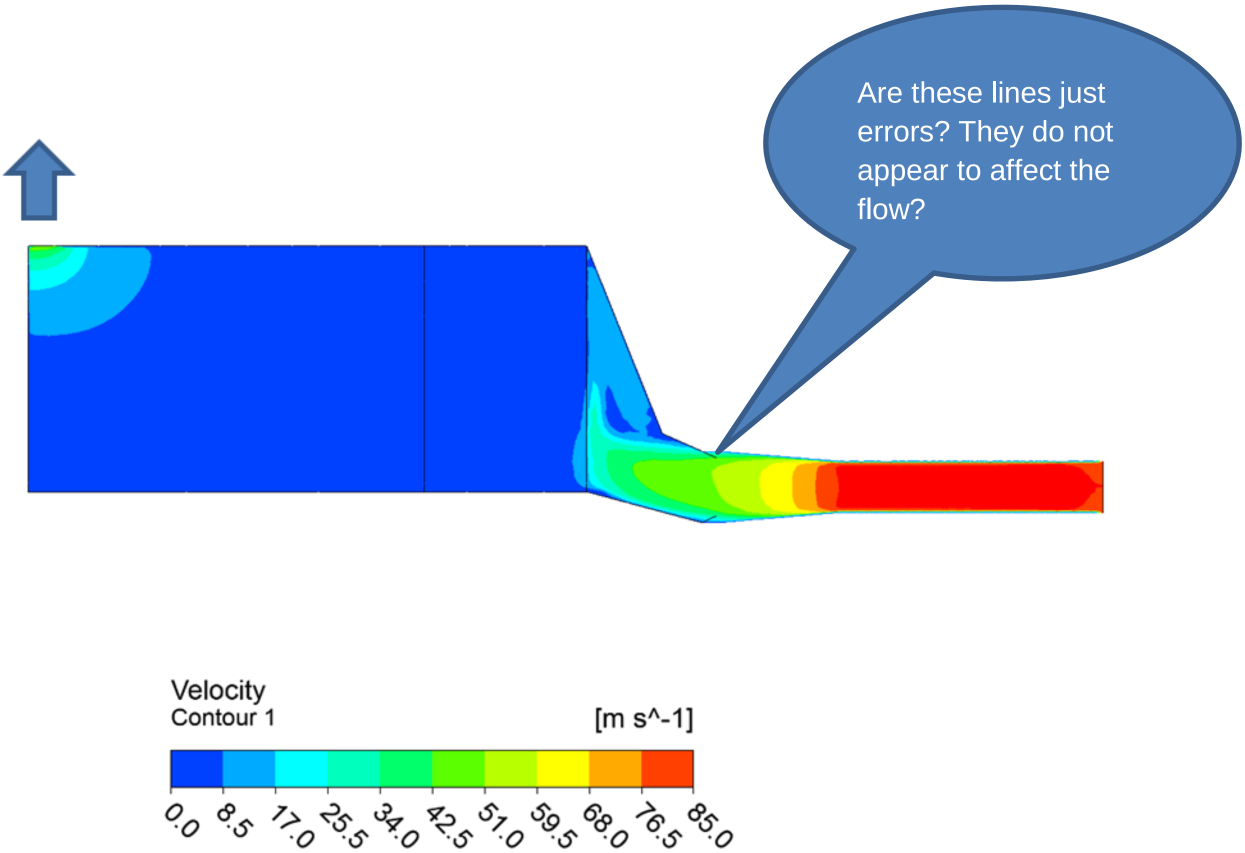


Figure 3:- CFD simulation showing predicted velocity contours along the central plane of the HRSG (Open topped).

3 Design of the HRSG.

The test programme for the WP 2.2 tests to date [1] has sought, amongst other things, to identify fuel composition boundaries entering into a fifteen tube bank heat exchanger that would result in no more than 2 barg over pressure downstream of the heat exchanger. Applying this constraint to the WP 2.3 rig design, and allowing for uncertainties in predicting accurately the likely over pressures, the HRSG containing section of the rig has been designed to withstand a minimum static pressure of 5 barg. Although the rig is intended to operate in the 400-600^{0}C range with short term higher temperatures due to the passage of the flame front, heat transfer calculations show that the wall temperature will not exceed 300^{0}C. The design of the proposed HRSG for Work Package 2.3 is shown in outline in Figure 4.

The rig is modular in design and construction, from the heat exchanger onwards to the exit stack and end wall. The rationale behind this approach is threefold, firstly tests can be carried out with the rig open to the atmosphere downstream of the heat exchanger, secondly further tests can be conducted with a wholly representative heat exchanger and stack assembly being present, and thirdly the number of rows of tubes in the heat exchanger can be changed in blocks of five, should the research indicate that this would be of interest.

The open-ended arrangement will allow some initial tests to be performed without the risk of excessive pressures being reflected back into the rig and causing structural damage to the rig itself. This arrangement will also allow comparison with tests undertaken in the open ended duct experiments of WP 2.2.

The stagnation pressure across the exiting wave front together with the side-on pressure will be measured using suitable pressure transducers. The release waves and the subsequent sideways movement of the gases immediately beyond the end of the HRSG exhaust duct should ensure that the pressures across the reflected waves will not reach the levels that may occur as a result of reflections from a fully enclosed system with a stack.

The effect of retaining the containment immediately downstream of the heat exchanger tube bank is that the flame front / pressure wave propagation will not begin to disperse into the free atmosphere until after the end of the HRSG exhaust section. This will ensure that values for the pressures immediately beyond the heat exchanger will be representative and can be measured accurately. It will also ensure that they can be observed with more certainty using the proposed arrangements than is currently possible with predictive methodologies. In particular this approach will enable more reliable estimates to be obtained of the high pressures that may occur when a pressure wave is reflected back from the enclosure walls and the stack. However an initially weak pressure wave that is by itself not sufficiently strong to damage the enclosure may, on passing through and exiting the heat exchanger, cause increased loading which becomes sufficient to cause damage when it is reflected back.

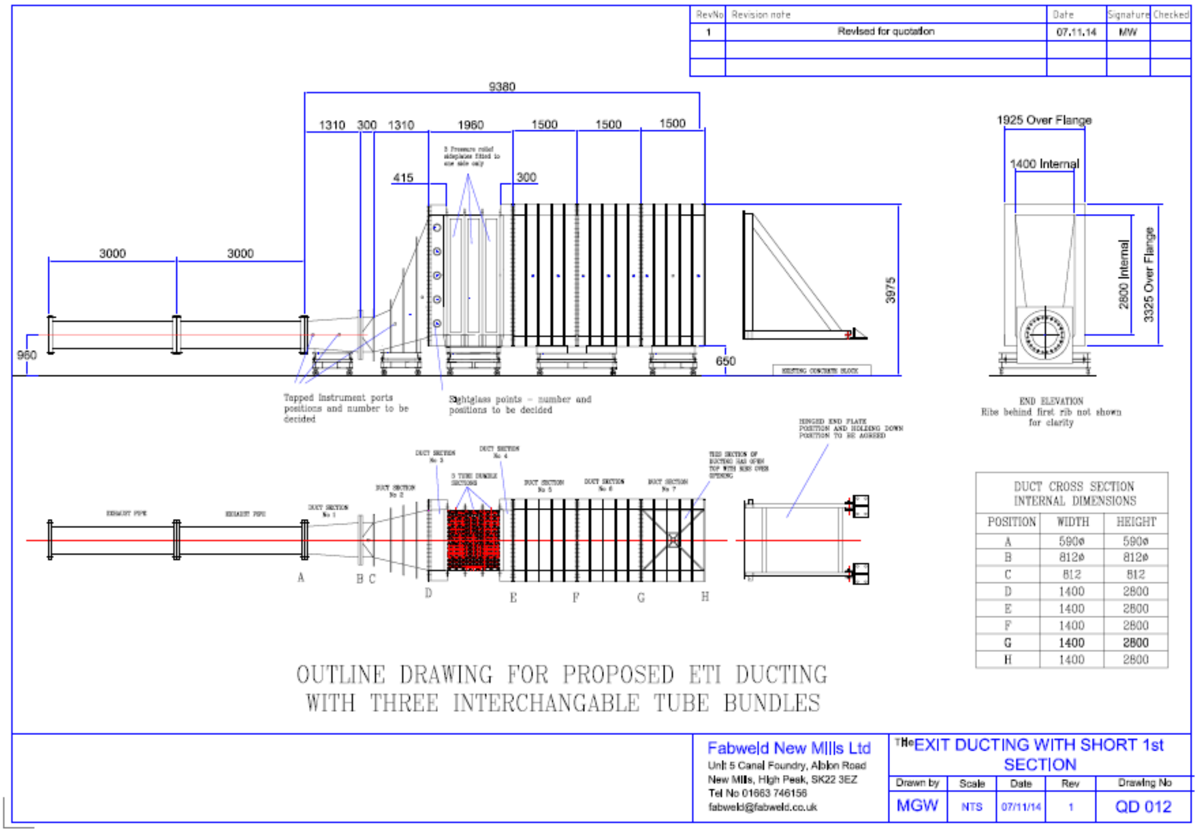


Figure 4 :- Proposed HRSG design (schematic).

The components forming the WP 2.3 rig comprise a conical expansion section (exhaust duct in Figure 1) which is attached directly to the end of the fourth section of the existing circular duct (WP 2.2). This conical section is then attached to a short section which transforms the circular inlet into a rectangular outlet section, as shown in Figure 4.This section has attached to it a rectangular expansion section (transition duct in Figure 1) which merges with the beginning of the HRSG. The HRSG contains a heat exchanger which comprises up to fifteen rows of tubes (in blocks of five) and is followed by a rectangular constant area section immediately downstream of the tube bank. See Figure 4. All of the components connecting the existing duct to the HRSG will be designed to withstand a minimum static pressure of 5 barg. This is to ensure that any pressure waves reflected back through the heat exchanger into the transition duct and then off its walls can be contained.

The proposed rig will be manufactured from structural steel EN 10028-P265 or a higher grade, rather than stainless steel. This produces a more cost efficient design with a large reduction in overall weight, but it will require additional maintenance against inclement weather in particular.

3.1 Circular duct section

The rig is approximately a one eighth scale model of an existing GE CCGT design, as discussed in the previous section, except for the first fourteen metres. Downstream from the turbine exit these will comprise the turbine exhaust flow control section, the transition section which contains the fuel and oxygen injection systems, the turbulence generator and the existing four consecutive three metre long sections of the 600 mm diameter circular duct from WP 2.2. This fourteen metre long section is equivalent to the turbine exit section shown in Figure 1.

The mass flow along the duct will be increased from the existing value in order to achieve the require flow velocity of 85 m/s. A suitable orifice plate will be used to control the flow rate.

3.1.1 Engine specification

The same R-R Viper gas turbine arrangement used for WP 2.2 will be used for the WP 2.3 tests. The velocity of the R-R Viper gas turbine exhaust products, injected fuel and make up oxygen, at the start of the expansion section will be 85 m/s. the exhaust gas temperature with injected fuel and make up oxygen will be 400 – 550°C, depending on the actual engine operating conditions being used.

The engine and butane systems are unchanged from WP 2.2 (circular duct rig)

The Rolls-Royce Viper Mk.301 engine is a single shaft axial flow turbojet that produces a maximum thrust of approximately 2500 lbs (1.136 Tonnes). The dry weight of the engine is approximately 250 kg. The two engines purchased originally for this particular research project were both previously installed on Hawker Siddeley HS.125 aircraft, a small business jet that was also used by the RAF for navigation training under the designation Dominie T-1. A conversion kit for running the engines on liquid butane was obtained from Reaction Engines, in order to reduce the amount of soot produced in the exhaust gases. To date one of the original engines has been damaged beyond economical repair during WP 2.2 testing, consequently two further engines have been purchased and they will be converted to run on Butane if and when required.

The engine is mounted on a frame manufactured by SCITEK, conforming to a standard design such that the centreline of the engine is approximately 0.95m above the floor of the concrete pad. The engine frame slides along a set of rails and can also be secured to them. This enables the engine to be moved backwards when necessary to allow access to the diverter section and also to be firmly mounted to the ground when testing. The mode in which the engine is run is not one that generates significant thrust as the exhaust nozzle has been removed.

A 24V electric starter motor is fitted to the underside of the engine, powered by two 12V rechargeable batteries connected in series. The starter motor raises the rotational speed of the engine compressor/turbine to approximately 800 rpm before fuel is introduced into the combustor cans of the engine via a flexible pipe coming directly from the fuel system's engine pump. The volume of fuel introduced and the starter motor operation is controlled remotely using SCITEK's control system, which utilises a National Instruments cRIO system (PLC). A number of engine parameters, such as the mass flow rate of air in the intake; the engine RPM, the oil pressure, engine vibration and exhaust temperature are also monitored by the cRIO.

A PC is used online to communicate with the cRIO while at the same time providing a user interface. The cRIO is housed in a 19-inch rack enclosure and also features engine start and stop buttons as well as other hard-wired safety systems.

The butane required to run the engine is stored 40 metres away from the engine in a single tank with a capacity of approximately 9000 litres. The tank was purchased new by HSL, and is fitted with a refill point, over flow valve, pressure relief valve, level sensor and excess flow valves. These components are the same or similar to those currently installed on a similar butane fuel system at Reaction Engines in Oxford.

The fuel is pumped from the tank via a boost pump towards the engine and through an existing 25 mm bore pipe. The boost pump specified for the fuel system is a 2.2 kW, M Pumps CT MAG-M6/2S coupled multistage peripheral pump with ATEX certification. This pump requires 3-phase power and is capable of moving approximately 2.5 m^3 of butane around the fuel system per hour.

Nearer the engine the pipe work splits into two lines, one returns fuel to the tank (25 mm bore pipe), the other (38 mm bore pipe) sends fuel to the engine. Approximately 30 minutes before the engine is due to start fuel is circulated around the return loop in order to ensure that all pipes are filled with liquid prior to engine start-up. At engine start-up a remotely actuated valve fitted to the engine frame is opened and fuel is allowed to flow through to the engine pump.

The engine pump is a 7.5 kW Hydra-Cell diaphragm pump model G25SMCTHFECA. This pump also requires a 3-phase power supply and is capable of achieving the pump's maximum flow rate of 2.5 m^3/hr at 629 rpm. The pump is fitted with a remotely controlled AC inverter, which allows its speed to vary. This therefore controls the fuel flow into the engine, effectively throttling the engine and controlling the engine speed.

Four remotely actuated valves are fitted at various locations around the system. Each valve actuator is ATEX certified and has ATEX limit switches fitted so that the open/closed position is relayed back to the control system. The first of these valves is located on the fuel line leaving the tank, the second immediately before the boost pump, the third on the return line and the fourth immediately before the engine pump. This final valve also acts as an emergency shut off valve in the event of the engine having to undergo an emergency shutdown. A number of pressure relief valves, manual valves and non-return valves are also installed in the system.

3.2 Fuel injection and supply system

The fuel and oxygen injection systems will remain essentially the same in principle as those used for the WP 2.2 duct experiments, the injection points remain the same but the actual mass flow rates of fuel and oxygen injected are greater than those used for WP 2.2.

The test rig requires the supply of mixtures of fuel gases, together with a separate oxygen gas supply system. These two separate gas streams will be contained in four (two by two) steel pressure vessels, each with a maximum capacity of approximately 225 litres and a MWP of 300 barg. Two vessels will contain oxygen only; the other two will contain the test gas fuel mixtures. These will comprise mixtures of hydrogen, methane and carbon monoxide. Specific gas mixtures and the oxygen supply will be prepared from individual gas cylinder packs using two separate Haskel booster pumps, Type 8AGD-30, and the mixture ratios quantified using partial pressures.

The oxygen and the gas mixture are injected directly into the engine exhaust stream and rely on the injection process to ensure that the gases are fully mixed as quickly as possible into this stream. The mass flow rates of the injected gasses are measured using individual coriolis mass flow meters, and controlled by mass flow controllers with the supply line pressures regulated using pressure regulators. Additional control and safety features are provided through the inclusion of stop valves, bursting discs and PRV's in the system.

The oxygen supply system has been installed and cleaned in accordance with European standards [2].

The WP 2.3 HRSG test programme will be undertaken with a constant mass flow rate in the duct of approximately 11 kg/s (this is approximately four times the mass flow rate used in the WP 2.2 test programme). The maximum v/v concentration of gas mixture or individual gases to be injected will be 15% and the minimum will be 4% v/v. In addition makeup oxygen can be injected at a rate sufficient to restore the oxygen levels in the exhaust stream to 21%. The gases injected are stored at ambient temperature and rely on the mixing process to heat them to the required operating temperatures.

Based on the experience gained from the design and operation of the current WP 2.2 test rig [3], it is expected that a complete test, from opening the supply valve, achieving the set mass flow rate, igniting the gas mixture, and closing off the fuel and oxygen supplies will last no more than twenty seconds. Consequently the quantities of gases stored will be doubled to 450 litres each and the quantities subsequently released will be based on the assumed injection time. The internals (valve trim sets) of the two mass flow controllers will be resized and new ones purchased to ensure that these valves can deliver the required range of mass flow rates. The maximum mass flow rate required will be 2 kg/s. Consequently the low pressure sections of the supply pipework (downstream of the H-H pressure regulator) will be increased in diameter in order to ensure that the pressure drops through the control valves are acceptable and that the required mass flow rates are achievable.

3.2.1 Ignition system and spark location

The ignition source will be the current 8 – 10 Joule spark plug source used in the WP 2.2 test series. The ignition source can be positioned at 250 mm from the beginning of any of the four 600 mm dia. tube sections, depending on the test requirements. The spark source will be positioned on the centreline of the duct, as is currently the case for the WP 2.2 test series.

3.3 Heat exchanger

The heat exchanger is designed to accommodate up to fifteen rows of tubes in blocks of five, to be followed by an open-ended rectangular section that represents the rest of the body of an actual HRSG. There is the facility to attach an additional rectangular section with a semi-open top to this section. The semi-open top represents the exit stack of the HRSG unit, having the same exit area as the scaled stack of the GE unit being modelled.

The heat exchanger is represented by a tube bank of five, ten or fifteen rows of vertical finned pipes. Each of the three tube banks will contain 73 tubes arranged in five rows and will be of carbon steel construction. The pipes will be 38.1 mm outside diameter steel tubing, with eight 0.4 mm thick ribbon wound fins per inch, wound at a 3.18 mm pitch, with an external diameter of 70 mm.

Each row of tubes will provide a blockage of approximately 40% of the total cross-sectional area of the heat exchanger. Alternative rows will be staggered from the previous ones to form the arrangement shown in Figure 5.

It is intended to make the heat exchanger as a separate unit, comprising three blocks of five rows each, these will be bolted to the end of the transition duct. This will provide a seal as well as allowing for thermal expansion. The heat exchanger tubes will run vertically. The three sections of 5 rows of tubes will be bolted together during construction and then finally welded on site when everything is in position. The heat exchanger unit will be supported on trolleys to allow for thermal expansion.

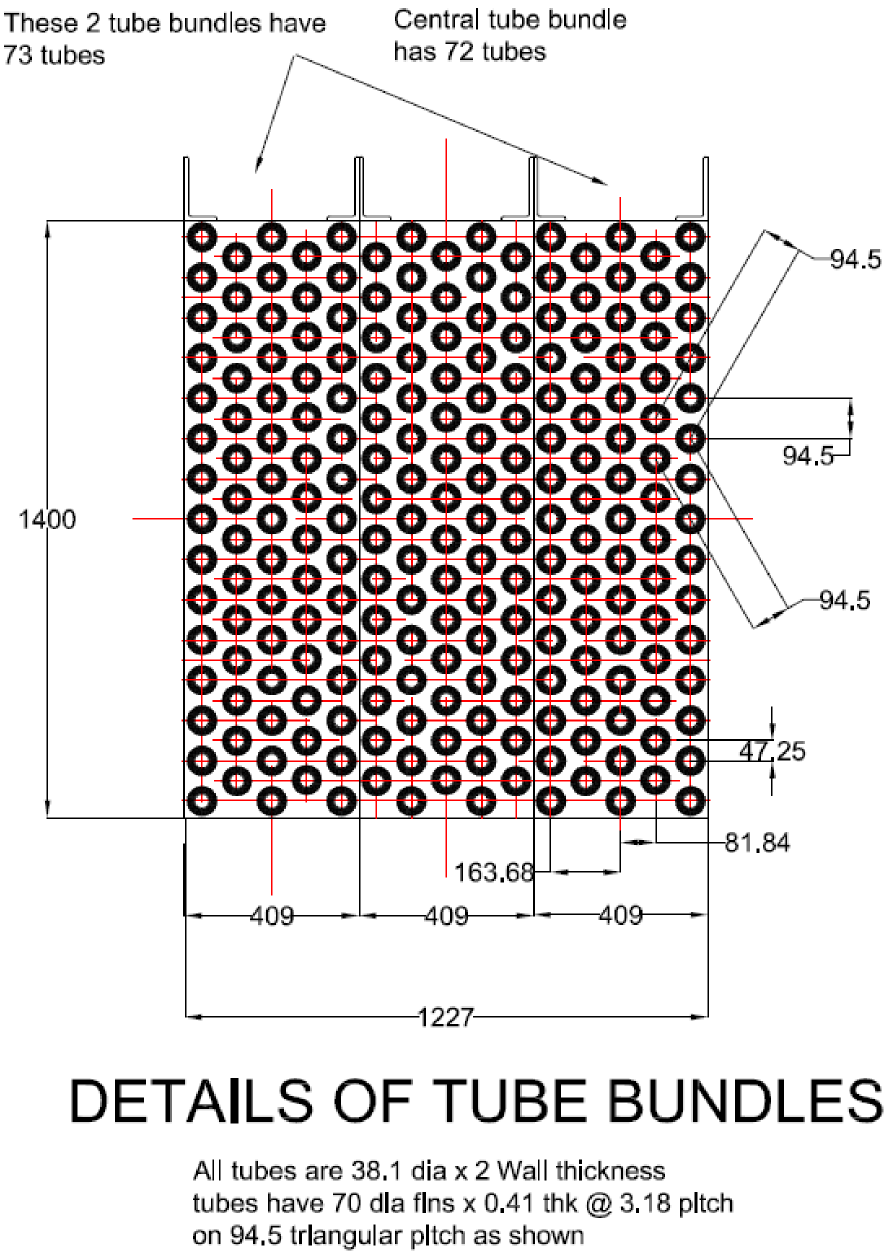


Figure5:- Proposed layout of the tube bank.

The heat exchanger arrangement uses standard finned heat exchanger tubing supported only at the top and bottom of the heat exchanger, but with the addition of high tensile steel rods running through each tube. The rods and tubes will be built in and welded at their bases but simply supported at the top of the unit to allow for thermal expansion. Structurally a single rod (manufactured from EN24) subjected to a uniform load should be able to withstand a 2% proof stress at a maximum stress of around 400 MPa at temperatures approaching 500 ^{0}C, based on the information given in [4]. If it is assumed that in the unlikely event of DDT occurring (WP 2.2 experience will inform how to avoid this) and the pressure generated builds up over at least 10 tube rows then the tube bank would be able to withstand a static pressure load of 5 barg in total. Higher loads would produce increasing permanent deformation until failure occurred at a load of approximately 10 barg.

The sides of the heat exchanger will contain six pressure relief panels on one side (LHS when viewed from the engine), each of which is designed to fail at 2 barg overpressure and thus relieve any relatively slowly rising excess pressures that may occur during operation. These panels may also be used to inspect the internals of the individual tube banks, should this be necessary.

3.4 Constant area duct

The heat exchanger, at the beginning of the HRSG module, is followed by an open-ended rectangular section that represents the rest of the body of the HRSG. There is a facility to attach an additional rectangular section with a semi-open top to this section. The semi-open top represents the exit stack of the HRSG. The latter section will be connected to the rig for some of the tests to provide further operational information.

The HRSG section will be constructed from 13 mm plate, supported by a series of external ribs as shown in Figure 4. The HRSG will be designed to withstand a static pressure of 5 barg at 400°C.

The completed CCGT model will be supported on bogies that will run on a new rail track with a wider track than the existing rail system. The new track will be some 16m long and mounting the CCGT on bogies will allow it to expand freely during operation as well as providing the means of moving the whole model downstream and away from the existing duct of WP 2.2. It will also be housed in an extension to the existing building to provide protection from the elements. Having the ability to detach and move the whole CCGT model out of the way of the exit from the 600 mm duct, means that either of the two rigs can be used independently of each other in the future with minimal effort.

3.5 End wall

An end wall together with an additional 1.5 metre long section can be added to the end of the HRSG to make the system more representative of an actual CCGT system, see Figure 4. The additional section will have a semi-open top and the wall will be anchored independently to the concrete base. This wall will be positioned at the end of the duct and will have a 20 mm thick steel plate attached. There will be mounting points for attaching pressure sensors centrally into the plate for recording the stagnation pressure of the incoming flow.

The wall will be designed to withstand a static pressure of 2 barg minimum, and will be anchored to the existing concrete base by a suitable support structure, backed up with a Pendine block wall.

This wall may also be used with the three metre long section of the HRSG, in which case it will be placed approximately 0.7 metres downstream from the end of it so that it will help to disperse pressure wave's emerging from the HRSG as well as allowing wave stagnation pressures to be measured.

An alternative wall design for this particular application may be utilised for measuring the side-on wave pressures.

3.6 Scaling

As mentioned earlier and based on the GE CCGT unit being modelled, the turbine exit velocity is taken as 85 m/s and the average uniform velocity after the heat exchanger as 6 -7 m/s. The former velocity is the turbine exit velocity, which reduces to approximately 55 m/s at the point of entry into the rectangular transition section of the HRSG. These two velocities are maintained on the proposed model together with the velocity immediately downstream of the tube bank, as can be seen from Figure 3.

3.7 Rig operation

The WP 2.2 test programme will help establish the range of fuel mixtures that upon ignition can be tolerated by the WP 2.3 test rig, i.e. relief from any higher pressures and the risks of backward moving high pressure waves, resulting from strong deflagrations or even from detonations.

3.7.1 Temperature

The complete rig will be designed to withstand wall temperatures not exceeding 300 °C. This wall temperature is justified, based upon the observed wall temperatures within the circular duct test programme of WP 2.2. The circular duct rig has been run for up to 15 minutes with wall temperatures not exceeding 300°C, despite being lagged.

The gas temperatures however have quickly reached temperatures of 550 – 600 °C, and when followed by an ignition event lasting no more than a couple of seconds the temperatures have momentarily reached around 1000°C.

Basic heat capacity calculations for the HRSG, which weighs around 20 tonnes and has a specific heat of 0.49 KJ/Kg.K, show that it would take 6.5 minutes to heat the HRSG to 400 °C, if all the heat of combustion from burning butane at 0.2 Kgs was used to heat the HRSG. This time increases to over three hours if the actual amount of heat transferred to the duct is used.

As a consequence of the foregoing, detailed heat transfer calculations for the HRSG have not been carried out, which in any case are not justified in the light of our experience with the circular duct and the results from the FE analysis of the HRSG (see section 3.11.2).

3.7.2 Flow velocities

It is envisaged that the WP 2.3 test programme with be conducted using a turbine exit velocity of 85 m/s in order to achieve an average velocity of 6 – 7 m/s after the heat exchanger.

The proposed operation will be similar to that being used for the existing WP 2.2 test rig. This requires the turbine exhaust velocity to be measured at the beginning of the second circular duct section, once a suitable operating temperature has been achieved. This will be done using a pitot-static probe traversed across the duct section as is currently being done for the WP 2.2 tests.

The exhaust mass flow can then be calculated together with the required injection rates for the fuel mixture and make-up oxygen injected for each individual test. These will be injected into the duct entrance using the same arrangement as is being used for the WP 2.2 test programme. The gas mixture is then ignited once steady state conditions have been confirmed throughout the HRSG.

It has been shown using CFD simulations, Appendix 1, that steady state gas composition conditions should be achieved in less than 3 seconds within the transition duct of the HRSG. It does however take over six seconds for the rig to be cleared of flammable gasses once the fuel supply has ceased.

3.8 Weather protection

The rig will also be housed in a weatherproof building (see section 3.12) which will be an extension of the current building housing the WP 2.2 test rig. It will be of a similar construction but will be taller at its apex (5.5 metres) and wider (6.4 metres), the latter to allow for operation of the LDA traversing system. The extension will extend by about one metre over the existing building and will be no more than 12 metres in length. All external surfaces of the HRSG model will be treated with primer and one coat of high temperature paint.

As with the previous circular duct rig [3] the WP 2.3 rig will not be insulated initially. However pins for attaching insulation and the provision of a protective canvas cover have been included in the rig costs, so that should insulation prove necessary during the commissioning programme it can be easily added as a variation at a later stage.

3.9 Access to instrumentation

Suitable walkways and access platforms will enable all of the instrumentation to be reached and maintained as necessary.

3.10 Ground works

The existing concrete pad will be extended by approximately 16 metres and an additional set of rails added. These will have a wider track than the existing ones. This is necessary because of the additional height of the HRSG. The extra length of the track will also allow the HRSG to be moved away by up to 6 metres from the existing WP 2.2 duct, thus maintaining the capability to use either rig in the future without compromising either. A distance of six metres is considered sufficient separation so as not to interfere with operation of the WP 2.2 circular duct rig as well as allowing room for maintaining it.

3.11 Structural analysis

3.11.1 Design standards

It is not considered practical to pressure test the complete rig or of individual components due to their size and shape. Design of the HRSG has therefore been undertaken by Fabweld, using established European Standards for the stresses of the materials and ASME VIII Div 1 equations / calculations to establish the stresses for thickness of the web material. Details of these design calculations are given in Appendix 2. The steel currently proposed for the ducting is EN 10028-P265 and that for the ribs is EN10025-S275JR (Higher grades may be used). The shell thicknesses for the individual sections shown in Figure 4 may vary between 20mm and 13 mm.

3.11.2 Finite Element analysis

A Finite Element (FE) analysis, has been undertaken of the response of the 3.0 metre long section of the HRSG structure immediately after the tube bundle when subjected to an internal deflagration. The analysis established the maximum static internal pressure that could be applied throughout the structure without causing substantial plastic strain. The maximum loading was found to be 8.5 barg before the model failed to converge. This is above the maximum design pressure of 7.5 barg (MWP X 1.5). At this pressure, the highest stress was 189 MPa , and the highest plastic strain was 0.4%. Obviously, plastic deformation has occurred, but the stresses and strains are well below those required to cause failure. The model also identified a requirement for diagonal strengthening at the four corners as shown. The results from this analysis are shown in Figures 6 and 7, which give the Von Mises stress criteria and the plastic deformation respectively.

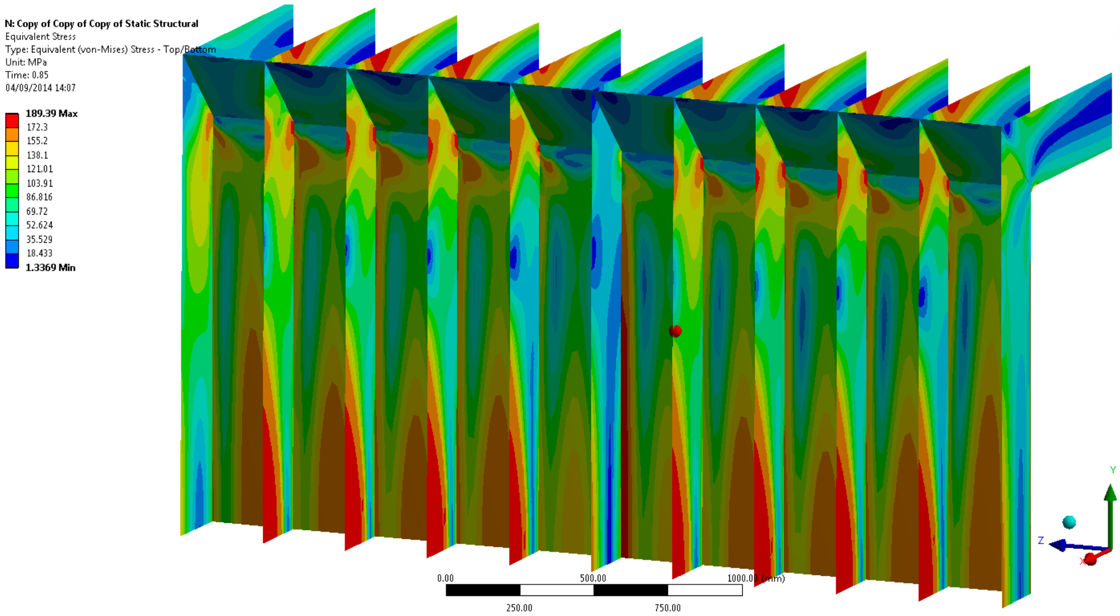


Figure 6:- HRSG stress analysis (Von Mises Criteria) for static load of 8.5 barg.

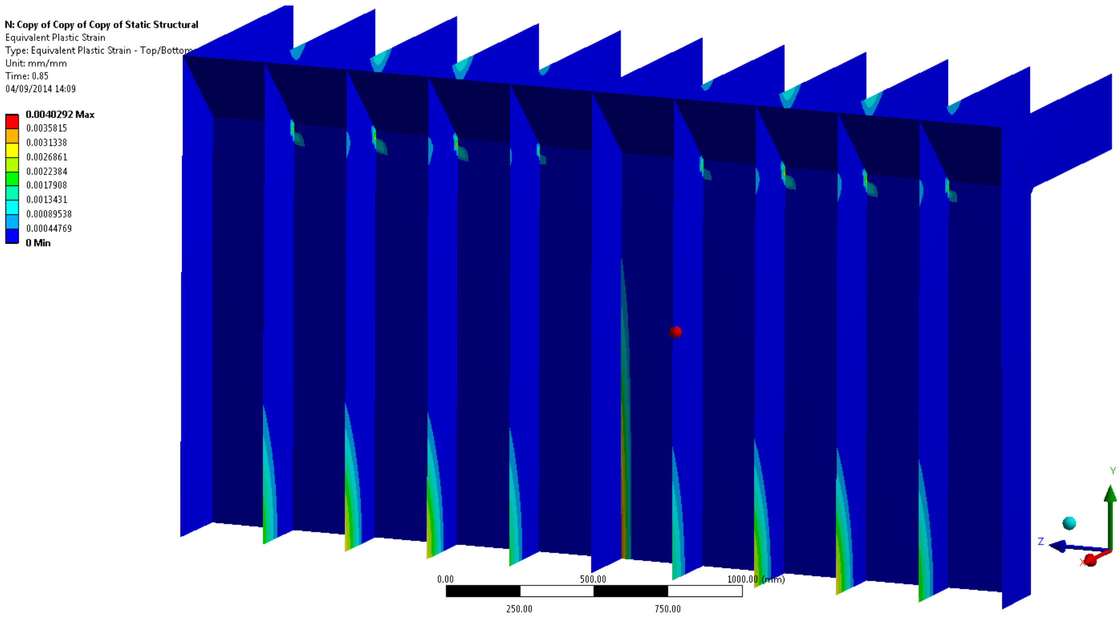


Figure 7:- HRSG Strains for a static load of 8.5 barg.

For high temperature use, the properties used were for P265 at 300^0 C, which has a proof strength of 173 MPa for thickness up to 16 mm, and 166 MPa for thicknesses between 16 and 40 mm. The elevated properties for S275 were assumed to be similar. For the model a yield strength of 170 MPa, was used together with a tangent modulus of 5000 MPa. It is expected that more strain hardening occur will occur when the yield reduces due to high temperatures.

If a design temperature of 400°C is used for the HRSG it would reduce the 0.2% proof strength by 13%, and thereby slightly increase the resultant strain but with stresses still below the UTS of the material at elevated temperature.

Although the rig is not designed specifically to withstand a stoichiometric hydrogen or methane detonation, a dynamic FE analysis of the heat exchanger structure has nevertheless been undertaken for such an event. The dynamic loads used were those predicted by the previous BAE systems analysis [5] of the 600 mm duct used in WP 2.2. The imposed dynamic loads were therefore a triangular pulse with equal rise and decay times of 9 micro-seconds each, and a peak pressure of 52 barg. A wave speed of 560 m/s was assumed, which is the theoretical speed of sound in the hot exhaust gases, this is conservative as the detonation wave front will travel at a higher velocity. A further analysis was carried out with the maximum pressure doubled to 104 barg to represent the reflection of the initial wave front from the back wall of the HRSG. The analysis was used to indicate the sensitivity to pressure of the structure for the typical detonation pressures anticipated.

The results showed that the peak stresses are about 80 MPa. The stresses alternate between occurring near the ribs, and then between the ribs. The results show the von Mises stresses for both stress patterns (there are no plastic strains to show). These are for models with mainly 25 mm ribs, and with 35 mm ribs at the ends of sections, but without any strengthening plates. Thus even at the higher pressure of 104 barg the structure was capable of withstanding the imposed dynamic peak detonation loads, as illustrated in figures 8 and 9 below.

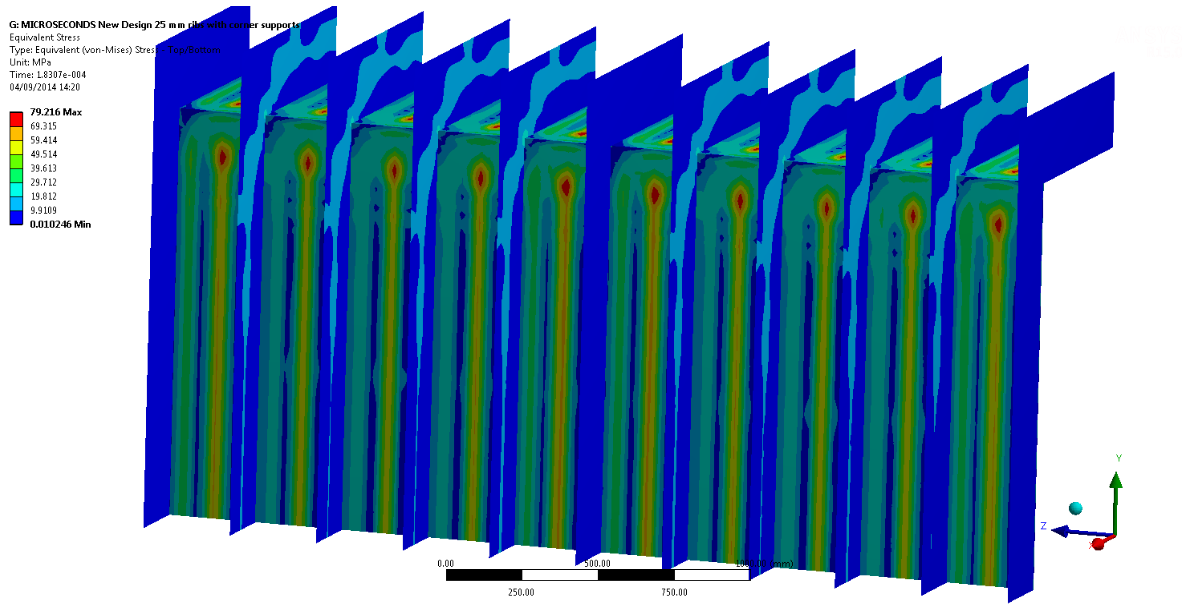


Figure 8:- HRSG stress analysis (Von Mises Criteria) for a dynamic load of 104 barg.

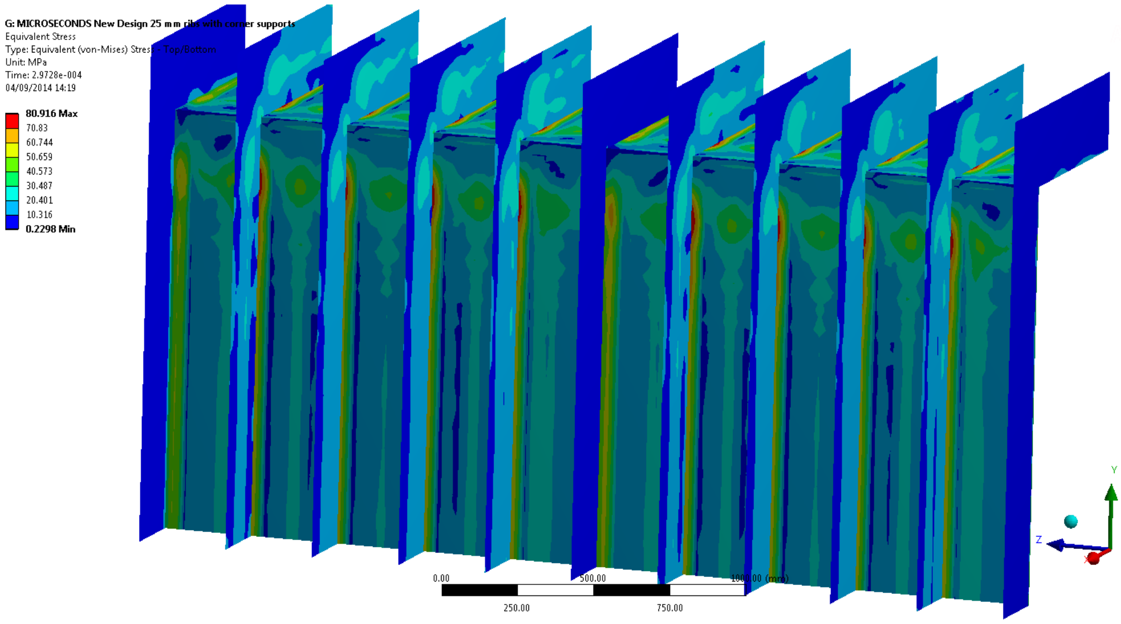


Figure 9:- HRSG stress analysis (Von Mises Criteria) for a dynamic load of 104 barg.

3.11.3 CDM

It is anticipated that all works described in this Basis of Design will be carried out under non-notifiable CDM. The labour costs to support this are included in the overall costs.

3.12 Blast mitigation

The Finite Element analyses presented in section 3.11.2 shows that in the event of a detonation occurring within the HRSG structure downstream of the HE the speed of the detonation wave passing through the HRSG is such that the inertial response of the structure effectively shields it from potentially damaging loads. This remains the case even if the detonation wave is reflected back from an end wall at twice the initial pressure, as illustrated in Figures 8 & 9.

An additional Finite Element analysis also showed that, when the design load is applied dynamically and maintained over a relatively long period of time compared to the detonation wave, the structure is still capable of withstanding the maximum anticipated overpressures, given in Table 1, at the intended operating temperature. In this case the levels of plastic strain were small (about 0.3%). Levels of stress reached a maximum of 172 MPa (just above the assumed yield of 170 MPa) about 3.6 ms after the pulse was applied, before dropping down to a steady 140 MPa following the initial overshoot. Although there will be a small amount of plastic set in the overall structure it will still maintain its integrity.

Based on these calculations structural failure and fragmentation is not likely to occur, hence ensuring safe operation and mitigating the need to contain the HRSG behind a blast wall.

ETI may wish to consider changes to the control system to mitigate the risk of any potential permanent deformation to the HRSG occurring as a consequence of the engine suddenly spooling down and a subsequent ignition occurring due to the test gas still being injected and ignited at a temperature below the minimum design temperature. A variation request covering blast mitigation will be submitted in due course.

3.13 Physical layout

Figure 10 below shows the physical layout of the proposed HRSG installation.

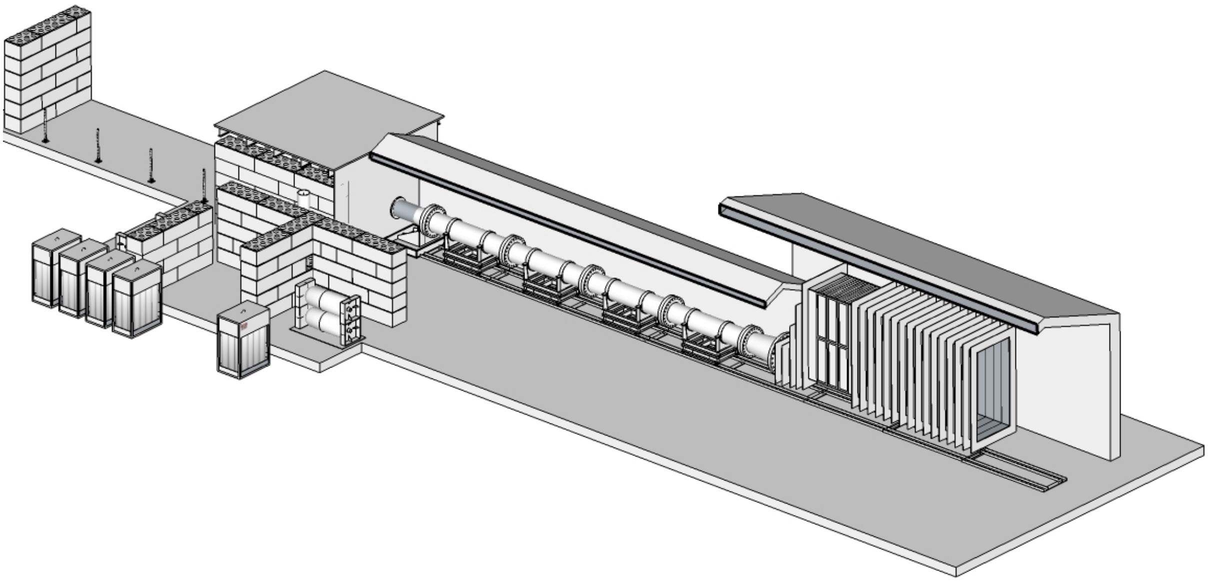


Figure 10:- Physical layout of the ETI rig with HRSG extension

The actual layout of the installation is shown in plan view in Figure 11 below.

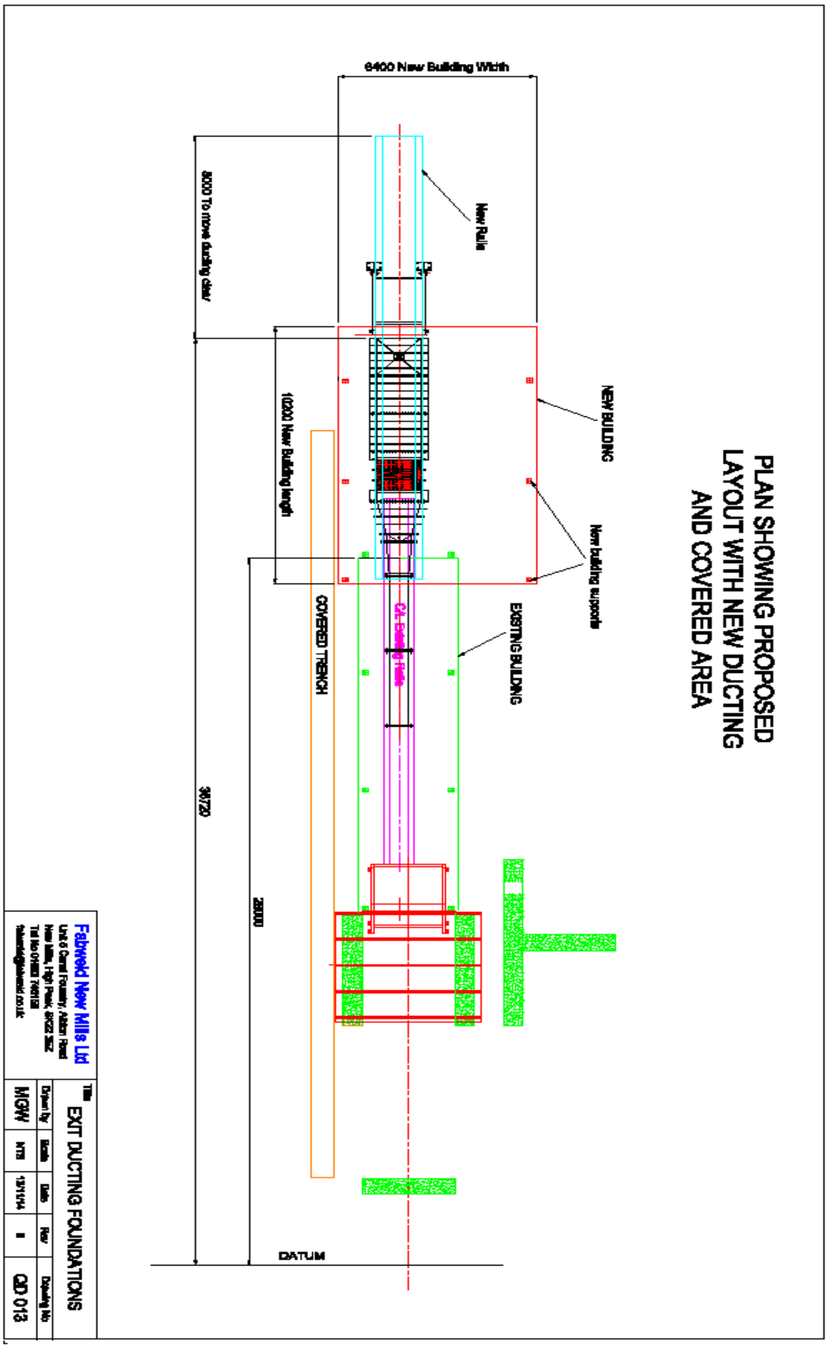


Figure 11:- Plan view showing proposed layout of the HRSG rig and enclosure.

3.14 Technical assumptions and calculations

In the proposed design, detonations within the rig will be avoided through a careful choice of fuel test mixtures based upon experience with the existing duct test rig (WP2.2), and potential changes to the control system.

The existing R-R Viper engine, diverter, fuel injection system and turbulence grid from the WP 2.2 rig, which have already been tested and commissioned, are being used as the basis for this the WP 2.3 rig. The approach will be that there will be sufficient control of the fuel injection rates to ensure that excessively high fuel mixture concentrations are not accidently injected into the rig and that the emergency shutdown procedures will ensure the safe dispersion of any flammable un-ignited mixtures.

Based on current understanding, it is assumed that ignition will be initiated in the second duct section, that a deflagration occurs and consequently the resulting pressure wave and flame front travel into the heat exchanger as it expands into and ignites the premixed gas mixture in front of it.

Based on information provided by A. Pekalski [6] the maximum stable explosion over pressures expected for both methane/air and hydrogen/air mixtures each with an equivalence ratio of one are as shown in Table 1.

Table 1:- Maximum over pressures for CH_4/Air and H_2/Air stoichiometric mixtures.

	Methane/Air Max explosion pressure (barg)	
T [C]	Deflagration	Stable Detonation
20	8.74	16.5
600	3.22	5.7

	Hydrogen/Air Max explosion pressure (barg)	
T [C]	Deflagration	Stable Detonation
20	7.95	14.95
600	2.9	5.08

It can be seen from the above that there is a substantial reduction in over pressures as the temperatures of the gases increase. As the rig is intended to operate in the 400-600^{0}C range it can be assumed that even in the worst case deflagration a maximum working pressure (MWP) of 5 barg will be sufficient to contain the event and maintain the integrity of the structure, even if a dynamic load factor of 2 is assumed. In the unlikely event of a detonation occurring in the 400-600^{0}C range the explosion pressures are expected to be in the range

5.0 to 6.0 barg which when the wave speed is taken into account will be contained by the structure as the FE analysis shown in Section 3.11.2 indicates.

It is clear from the information provided by the industrial sponsors that HRSG pressures above 2 barg will not be acceptable in practice as they are well above the typical pressures that existing CCGT/HRSG structures can withstand in the event of an ignition and subsequent deflagration. Thus to give a margin of safety a maximum design pressure of 5 barg has been assumed for the HRSG section of the rig. Consequently the design pressures used for the various sections of the rig are based upon what are considered to be achievable without producing an excessively heavy and costly design. Increased pressure ratings (if utilised) for exhaust and transition duct sections would reflect the possibility that the pressures associated with any waves reflected back into these sections may increase in magnitude as a result of the geometrical arrangement of the transition section acting in reverse.

3.15 Calculations supporting the 600 mm duct

The WP 2.3 test rig will use some of the existing components from the WP 2.2 rig as mentioned in the previous section. The key components being used are the first two sections of the duct, which have an internal diameter of nominally 600mm and are capable of withstanding a static pressure of 22 barg maximum, combined with a maximum wall temperature of 400^{0}C.

The duct is also designed to comply with ASME B31-3 Pressure Piping code [7] and ASME B16-5 Flange Code [8]. In addition all components comply with the Pressure Equipment Regulations 97/23/EC [9].

It is assumed that the engine exhaust cone and supporting vanes may be subjected to an impulsive reaction due to a static pressure not exceeding 5 barg acting along the pipe centreline towards the gas turbine. The duct mounting system may also be subjected to this pressure load.

Turbulence generator: this is situated at the entrance to the duct and can withstand in shear an impulsive pressure load of 22 barg acting normally across the full section.

Tubes/ flanges and transition section design: all of these components are designed in accordance with ASME B31.3 Pressure Piping Code [7], with the maximum allowable working pressure at 400^{0}C being 23.9 barg (which is adequate to meet requirements). The theoretical burst pressure of the tubular duct sections is 140 barg.

Forged flanges, (certified) according to ASME B16.5 in 304L of 300lb dimensions are rated at 23.9 barg at 400^{0}C and are therefore adequate. These flanges are 914 mm in diameter for a 600 mm pipe. The flange thickness is 111 mm and the weight of each three metre long section of completed tube is 1.5 Tonnes.

The use of this tube size also allows for any unforeseen significant overpressures in the unlikely event of DDT occurring, when very short durations/transient dynamic pressures pulses may occur, with an average pressure of 30-40% in excess of static loading. The relevant design calculations are given in Appendix 3.

The design pressure was obtained from the numerical modelling simulations undertaken under contract by BAES [5]. These assumed that a hydrogen detonation occurred under stoichiometric conditions for which the predicted maximum pressure was 22 barg, with peak pressure spikes some 2-5 times greater but lasting for around 10 micro-seconds. Consequently these peak values may be ignored as their duration is well below the period of the natural ringing frequency of the tube, which is $3X10^{-4}$ seconds. This was also confirmed through dynamic finite element calculations simulating the impact of the loading conditions predicted by BAES.

Two sets of injection tubes, each comprising six entry points, are provided in the walls of the transition section. These are close together at the engine end of this section and provide the means of injecting the fuel mixtures and oxygen into, and mixing with, the main exhaust flow from the engine. The relevant calculations are at Appendix 4.

Instrument ports: The bosses are 50mm in diameter and are welded directly to the outside of the tube sections in accordance with the ASME code.

Diverter section: This section is designed and manufactured from 304L stainless steel, to provide a range of input mass flow rates in accordance with the design specification for the WP2.2 rig. It provides a means of restricting the inlet flow to the duct by spilling excess flow through two 300mm diameter side exhaust pipes, which are situated before the duct entrance. The flow rates and operating temperatures are controlled by orifice plates situated at the beginning of the transition section. The current design for the WP2.3 rig utilises two orifice plates, dimensioned such that a velocity of 85 m/s can be maintained in the duct but at two different temperatures. This item is designed to withstand a static pressure of 5 barg.

Anchor plate: This comprises both the attachment to the tube at the interface section and the mounting to the concrete base underneath the containing tunnel. The reinforced concrete base is located 1.00 metre below the centre-line of the test rig and its dimensions are 32 x 3.25 x 0.375 metres. It weighs some 94 Tonnes. Calculations for the anchor plate design and the attachment bolts to the concrete base are given in Appendix 5.

3.16 Injection rates for test gases

The calculation procedures for the maximum and minimum gas and oxygen flow rates required to give up to 15% v/v in the exhaust flow of 11kg/s and replenish the oxygen level to 21% are shown in Appendix 6. The calculated values are as follows: - Oxygen: 0.82 kg/s. Hydrogen: 0.144 – 0.038 kg/s. Methane: 1.149 – 0.306 kg/s. Carbon monoxide: 2.0 – 0.523 kg/s. The resolution of the measurements is expected to be better than 0.5% of FSO, and the Emerson control system is designed to reach the desired steady flow rates within 5-10 seconds. If the maximum oxygen and fuel mixture are introduced at ambient temperature into the 500^0 C exhaust then the exhaust temperature may fall by no more than 100^0 C once the gases are fully mixed. See also Appendix 6.

Valves and piping have been sized in order to give acceptable pressure losses throughout the two systems (oxygen and the gas mixtures). A pressure of approximately 20 barg has been assumed as the pressure at the injection points.

If the mass flow rate from the system is 11 kg/s at 500^0 C then the velocity of the flow will be 85 m/s. When the engine is idling at a mass flow rate of 5 kg/s and the majority of this flow is diverted out of the test section the velocity reduces to 10 m/s in the duct section. The corresponding residence times in the duct are 0.15 to 1.2 seconds and the Reynolds Numbers for the maximum and minimum flows are $6.2X10^5$ and $0.7X10^5$ respectively, showing that the flows will be fully turbulent.

Design of gas and oxygen injection and mixing systems: The design of these two systems is based upon the experimental results given in [10]. This paper provides an experimental correlation for both the centreline velocity and concentration decay for highly under-expanded gaseous jets as a function of downstream distance, pressure ratio and nozzle diameter.

The axial velocity decay correlation parameter (Q) is :-

$$Q = 0.08(1 - 0.16M_j)\left[\frac{\rho_a}{\rho_{eq}}\right]^{0.5} Z/R_{eq} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The axial concentration decay correlation parameter (C) is :-

$$C = 0.104(\rho_a/\rho_{eq})^{0.5}(Z/R_{eq}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:- $\rho_{eq} = \rho_c(P_a/P_c)$ and $R_{eq} = D_{eq}/2 = D_j(P_e/P_a)^{0.5}$. Subscript c refers to choked conditions at the orifice exit, where for a sharp edged orifice or convergent/divergent nozzle M=1.

Thus from graph (figure 3) in [10], Q = 15 for a velocity decay to 10%. Then assuming a stagnation pressure of 20 bar the downstream distance to this velocity is 993 mm for an orifice diameter of 2.5 mm.

The equivalent concentration decay from graph (figure 4) in [10] is C = 15. This gives a distance of 652 mm for an orifice diameter of 2.5 mm.

In all cases it is assumed that the jets decay at an angle of 7.5 degrees. Therefore at a distance of 1000 mm downstream, assuming a Gaussian profile, the width of the dispersing jets will be about 280 mm diameter.

Using the maximum flow rates as specified previously it can be shown, *by way of an example,* that for the injection of hydrogen through a sharp edged orifice (C_D=0.5) some 156 holes of 1.59 mm diameter are required. For CO and CH_4 similar hole sizes are required. In the case of oxygen again some 156 holes are required of 1.89 mm diameter.

It is intended to inject the gases through spray tubes such that the gases are injected circumferentially across the duct in order to enhance the rate of mixing. It is also intended to inject the oxygen immediately before the gas mixture, thus allowing it to mix and cool the exhaust gases at about the same time that the gas mixture is injected. The spacing of the injection orifices will be such as to ensure that a constant mass flux across the whole of the cross-section of the duct is achieved. A CFD analysis of the injection process was modelled using indicative data, in order to ensure that the system design was satisfactory and that adequate mixing was achieved. The results are given in [11], they showed that at the maximum velocity used in the study mixing was successfully achieved within 4 metres of the injection point. This distance was confirmed experimentally for the proposed test velocity of 85 m/s by examining the mixedness of the injected gases; see the commissioning report [12].

4 Instrumentation

We are currently putting together a Variation Request, looking at all aspects of the HRSG instrumentation following discussion at Stage-Gate 3. The first option will be to use the sensors that are currently being used on the circular duct rig. At present, the data collected from the recently WP 2.2 test programme is being analysed with a view to assessing the performance of the current sensors and their suitability for use on the WP 2.3 rig, especially when operating at low EQR's.

Further options are being considered, including additional optical and ionisation probes, fast response thermocouples, and the use of high speed video cameras to provide qualitative information on the passage of the flame front.

As it stands at present we will be using the existing instrumentation from the WP 2.2 circular duct rig. It consists of the following:-

- 24 Ionisation wall probes.
- 6 Optical probes.
- 6 Kulite type pressure transducers.
- 12 'K' type thermocouples.
- 1 Pitot-static probe.
- 1 Oxygen gas analyser.

Fifty ¾ BSP instrument ports will be included in the final design. These numbers of ports being considered sufficient to allow flexibility in the positioning of instrumentation once the test programme commences. The majority of these ports will be installed on-site, thus allowing time for any feedback from the existing WP 2.2 test programme to be incorporated into the design and location of these instrument ports. Additional instrumentation ports can be readily installed on-site once the rig is completed or during manufacture, should additional instrumentation be agreed as part of the variation request.

4.1 Engine Instrumentation

The engine instrumentation is unchanged from WP2.2 (circular duct rig), and is instrumented in three parts, the intake, the Viper Type 301 engine and the diffuser/transition. At the intake the mass flow rate of air entering the engine is measured so that the air/fuel ratio can be calculated. Additional exhaust mass flow measurements are derived from pitot-static probe measurements taken across the beginning of the second duct section.

To determine the air mass flow entering the engine a specially designed intake (based on methodology recommended by Rolls-Royce) is used. The intake features static pressure tapings at its throat and by measuring the static pressure during operation the mass flow can be calculated. The engine intake mass flow measurements are reported in [13].

Six engine parameters are monitored to track the engine health when in use, the engine RPM, the butane fuel flow and pressure, the engine oil pressure, engine vibration levels and the compressor delivery pressure. A frequency generator on the engine sends a signal that is proportional to the engine RPM back to the control system where it is interpreted. The butane mass flow rate is monitored via a turbine flow meter located on the engine.

A Druck PTX1400 pressure transducer with a maximum range of 50 bar is situated upstream of the flow meter for safety purposes; for example if the fuel pressure recorded falls outside of the operational limits an emergency shutdown of the engine will be triggered. Lastly two further Druck PTX1400 pressure transducers with a maximum range of 10 barg are fitted to the engine in order to monitor the oil and compressor delivery pressures. A 50g accelerometer is used to monitor engine vibration.

The diverter and transition sections expand from an annular geometry immediately aft of the turbine through to a cylinder at the interface with the pipe section. The temperature of the gas exiting the turbine is monitored to ensure that the engine is not operated outside its safety limits. Three K-type thermocouples with a maximum temperature rating of 1100 °C are used for this purpose and have been inserted into the air stream through equally spaced ports around the circumference of the turbine diffuser.

The engine control system monitors all of the parameters described here. If, for example, an over temperature in the exhaust or an over speed in the engine RPM is detected the control system automatically cuts the fuel supply to the engine. This is necessary in order to ensure the longevity of the engine and its safe operation.

4.2 Butane Fuel System Instrumentation

The butane fuel system is unchanged from WP2.2 (circular duct rig). The Viper engine is fuelled from an on-site butane supply, with a water capacity of approximately 9000 L, situated 40 m away from the test site. The amount of fuel remaining in the tank must be known during testing so a level sensor has been installed in the tank and the data recorded fed directly into the control system.

The two pumps feeding the Viper engine with butane are a boost pump and an engine pump. The boost pump rotates at a constant rate, thus a remotely operated on/off switch is used to control it. The engine pump, manufactured by Hydra-Cell, is fitted with a 3-phase inverter so that varying the pump speed can control the flow of fuel into the engine. The pump RPM is monitored remotely by the control system whilst it is in operation.

The four remotely actuated ball valves in the butane fuel system are fitted with two ATEX rated limit switches that return a signal to the control system when activated. This allows for remote monitoring of the open/closed status of the valves. Finally, to ensure the safe operation of the butane fuel system, a Druck PTX1400 ATEX rated pressure transducer has been installed between the boost pump and the engine pump (immediately before the shut off valve). With a range of 0 to 25 barg, this sensor sends a 4-20 mA signal to the control system allowing the system pressure to be monitored remotely. The signal from the pressure transducer is also monitored by the emergency stop system, which will be activated if the fuel pressure falls outside of the pre-defined operational limits. The butane supply system has been installed in accordance with the relevant code of practice, [14].

4.3 Gas Delivery System Instrumentation

The mixtures of Hydrogen, Methane and Carbon Monoxide and the Oxygen injected into the engine exhaust stream are obtained from standard pallets of the individual gases, which are at pressures up to 200 barg, depending on the particular gas. Gas mixtures are prepared using a Haskel boost pump to supply individual gases to the storage vessel. The desired mixture concentrations are obtained by measuring the partial pressures of the gases as they are pumped into their mixing vessel. The gas mixture is then circulated for up to one hour to ensure that the gases are adequately mixed. The mass flow rates of the fuel gas mixtures and separately the oxygen mass flow rates that are injected into the engine need to be measured and controlled to a high level of accuracy. This is done using primarily coriolis mass flow meters whose outputs can be checked against load cells mounted under the storage vessels. The load cells measure the mass flow rates directly whilst the coruolis meters are linked to the pneumatically controlled mass flow control valves.

5 Project Management

Critical activities/timings (ETI in Red)

Issue final BoD to ETI
Due date: 11/11/14

ETI approval of BoD
Due date: 21/11/14

HSL submit Variation Request outlining cost for manufacturing and installation element of HRSG rig build (excluding HRSG instrumentation and blast mitigation – see below).
Due date: 25/11/14

Approval from ETI to start Fabweld manufacture of HRSG
Due date: 28/11/14

Issue proposal/Variation Request for HRSG instrumentation options
Approval from ETI on HRSG Instrumentation
Due date: 24/12/14
This is a risk area as this time line is during Christmas.
Approval from ETI for HRSG instrumentation Variation Request
Due date: 07/01/15

HSL issue proposal/Variation Request for blast mitigation measures
Due date: 05/12/14

Approval from ETI for blast mitigation measures
Due date: 19/12/14

Completion of circular duct test programme (date when ground works for HRSG must start)
Due date: 03/02/15

HRSG manufacture completion date
Due date: 17/04/15

Start of commissioning on HRSG
Due date: 05/05/15

Start of test programme HRSG
Due date: 06/07/15

6 References

1. WP2.2 Test Plan. H. Michels, and S. Hawkesworth. September 2014
2. European Industrial Gases Association document IGC 33/97/E 'Cleaning of equipment for oxygen service'.
3. BoD for WP 2.2 Circular duct rig. March 2014.
4. Elevated Temperature and High Strain Rate Properties of Offshore Steels. SCI for HSE. OTR 2001/020.
5. Modelling of Blast in Hydrogen Power Generation Systems, Ricardo Rosario, July 2012, BAE Systems, report TES 109464.
6. Determination of the explosion behaviour of Methane and Propene with Oxygen in Standard and Elevated Conditions. A.A. Pekalski, et Al. Trans I. Chem. E 2005.
7. ASME B31-3 Pressure Piping code.
8. ASME B16-5 Flange Code.
9. Pressure Equipment Regulations 97/23/EC.
10. "Jets discharging to atmosphere." K. Moodie & B.C.R. Ewan. J. Loss Prev. Process Ind. 1990. Vol 3. January.
11. ETI High Hydrogen – CFD Analysis Of The Task 2 Rig Gas Mixing System, Daniel Veen and James Linfield, 16/06/2013, document number STK00342
12. Commissioning report WP2, K. Moodie, B.C.R. Ewan & M. Christdoulou, March 2014.
13. Viper Intake Mass Flow Calibration Report, SCITEK, M. Christdoulou, 29/11/2013. Report number STK00381, Issue 1.0
14. UKLPG Codes of Practice for the Installation and siting of butane tanks, associated pipework, valves and safety devices.

Appendix 1:- Power point presentation of CFD flow simulations. HSL rept. 2014.

Appendix 2:- HRSG design calculations (separate document)

Appendix 3:- Tube structural strength calculations (separate document)

Appendix 4:- Design calculations for interface section (separate document)

Appendix 5:- Design calculations for anchor points (separate document)

Appendix 6:- Gas Turbine Mass Flow Calculations.

Appendix 1:- CFD simulations.

Contents

- ## Objectives
- To provide indicative CFD predictions of the flow through the duct leading to the finned-tube heat exchanger
- To demonstrate that the flow exhibits similar behaviour to the full-scale GE duct.
- To assess the impact of varying the pressure drop through the heat exchanger (from around 750 Pa)
- To perform transient simulations showing ingress of (H_2 + air) mixture into duct that is initially full of exhaust gases

Methodology.

Base Case Model Configuration.

Inflow: Gas velocity is 85 m/s, at a temperature of 550°C. The turbulence intensity, as measured for these flow conditions, is13%. The Eddy viscosity ratio is 100.

Gas composition: Stoichiometric H_2 combustion gases (65% N_2 + 35% H_2O.

Outflow: Constant pressure boundary with two configurations 1) the HRSG is open ended and 20 the outflow is through a slot at the top end of the HRSG, this represents the exit stack.
Walls: No-slip, smooth. Max wall temperature is 300°C
Turbulence model: Is SST with standard buoyancy corrections.

CFD software: ANSYS-CFX version 15.

The base model configuration is shown below:-

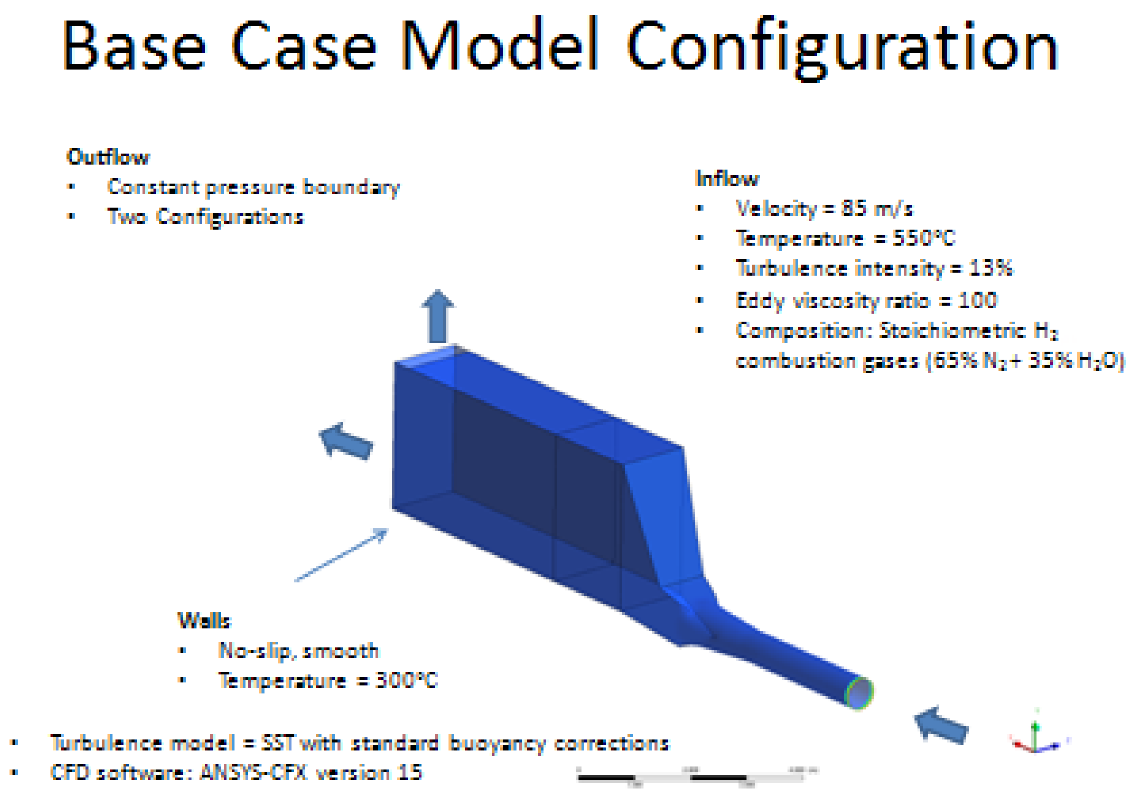


Figure A1:- Base model configuration.

Geometry.

The design of the scaled HRSG is shown below. It is taken from Figure 4 of the BoD.

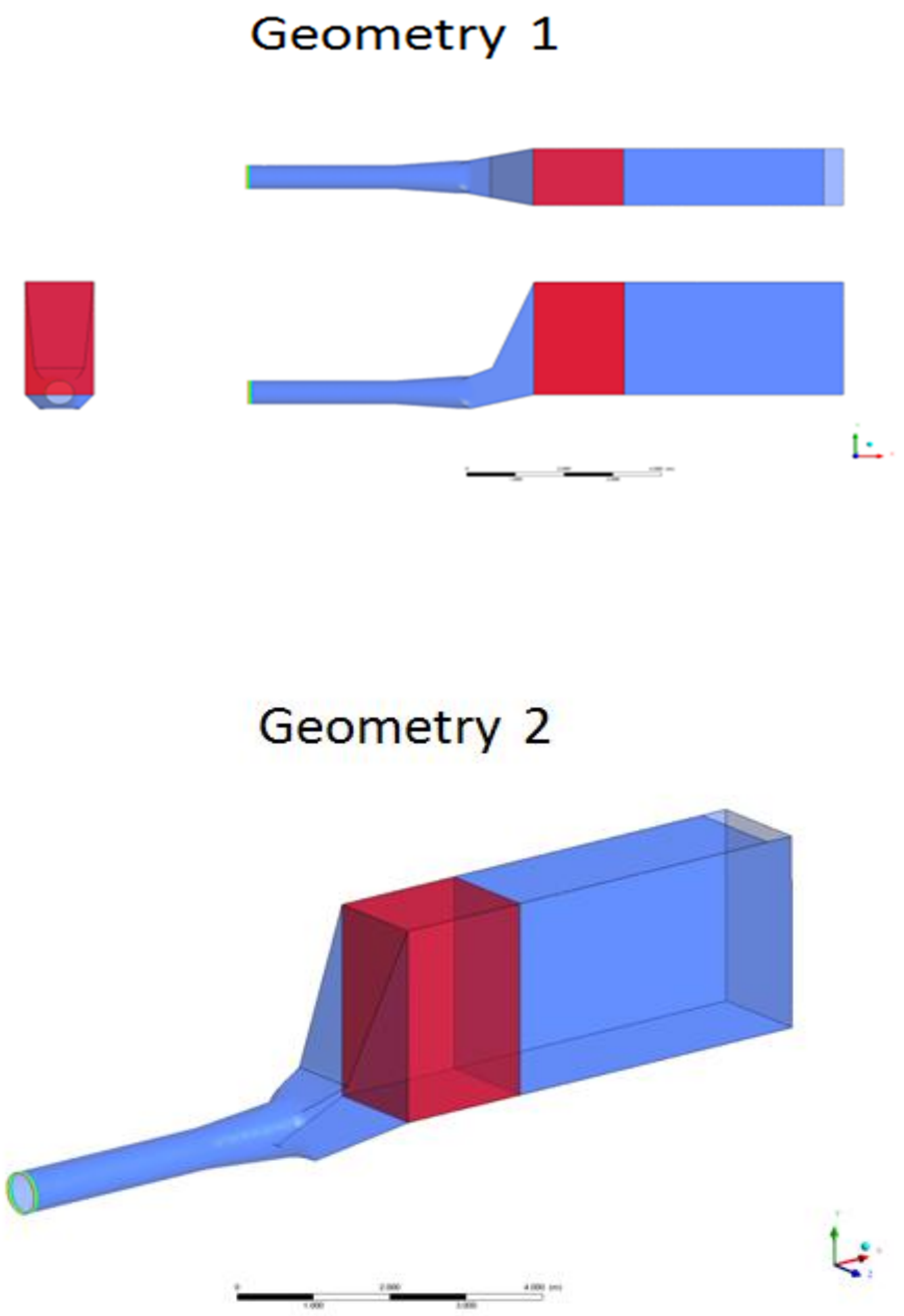


Figure A2:- Geometrical representation of the scaled HRSG, taken from the design drawing Figure 4 of the BoD.

Heat Exchanger Modelling.

Resolving flow around each tube requires very fine grid, even when fins are ignored, >12M nodes are needed for a coarse grid. It is not feasible to use this approach due to the computing time required

Solution: Porosity used to approximate flow resistance of finned-tube heat exchanger. The Sink term in momentum equation: $S = -\frac{1}{2}\rho K|U|U$. Loss coefficient (*K*) chosen to achieve pressure drop of $\Delta P \approx 750$ Pa. Sensitivity tests results shown later to assess effect of varying *K*

Porous region with prescribed flow resistance used to represent finned-tube heat exchanger, as shown by red arrow in Figure A3 below.

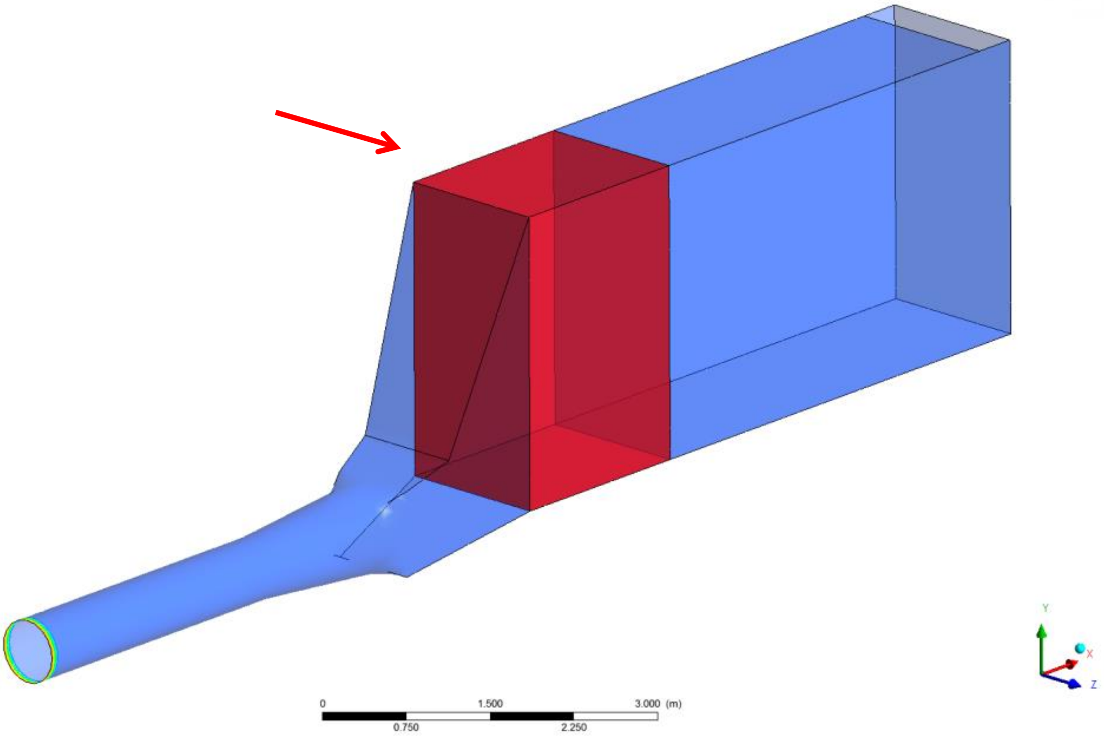


Figure A3:- Area of model porous region that represents the tube bank (15 rows).

Grid Sensitivity

Comparative runs were undertaken using two different grids as shown below in Figure A4 a-c. As expected the finer mesh produces what is consider the more representative flow simulations.

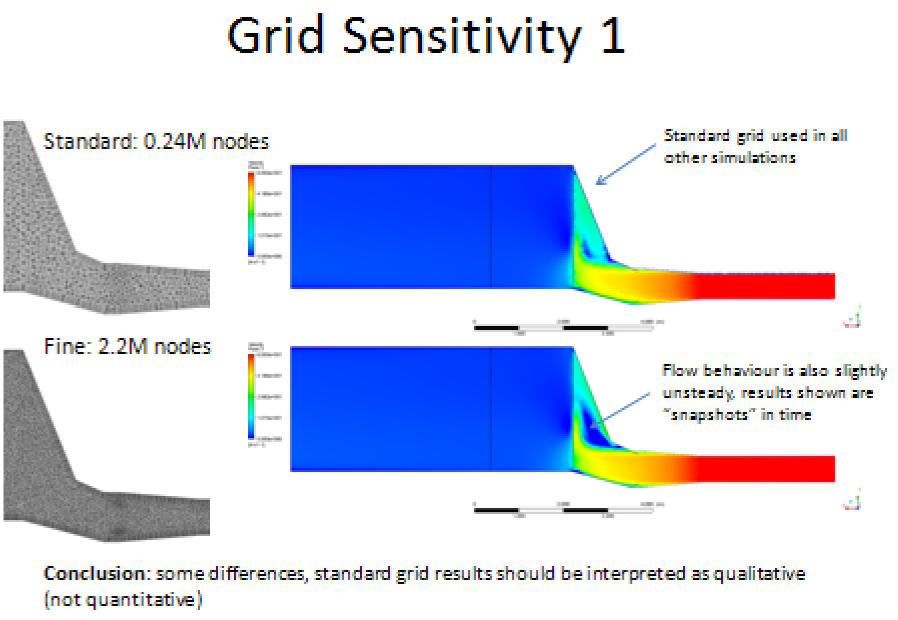


Figure A4a:- Grid sensitivity results (Velocity contours open ended).

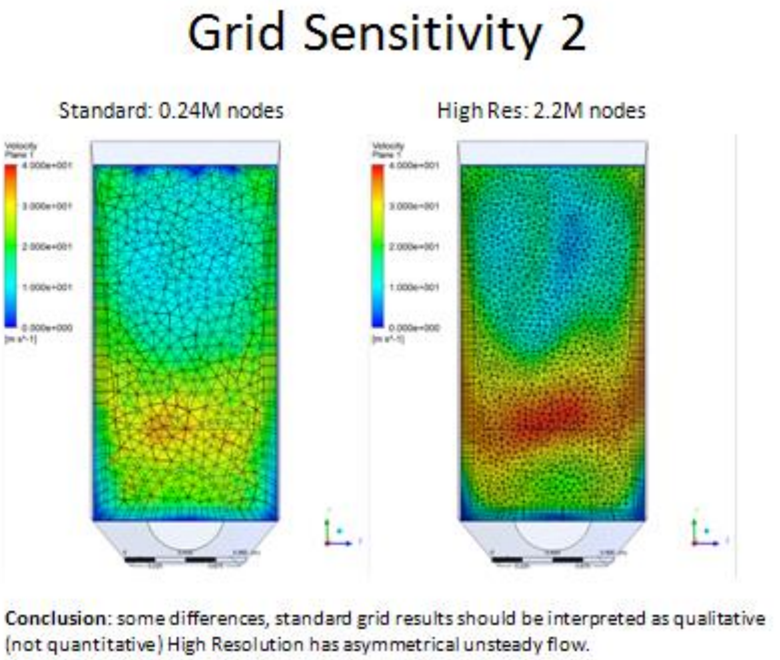


Figure A4b:- Grid sensitivity results (Velocity contours across entrance plane).

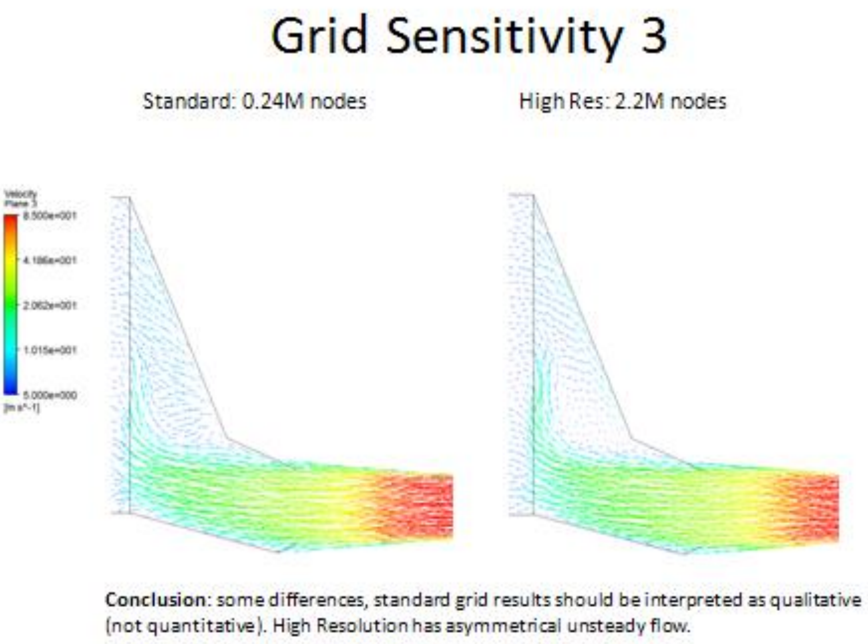
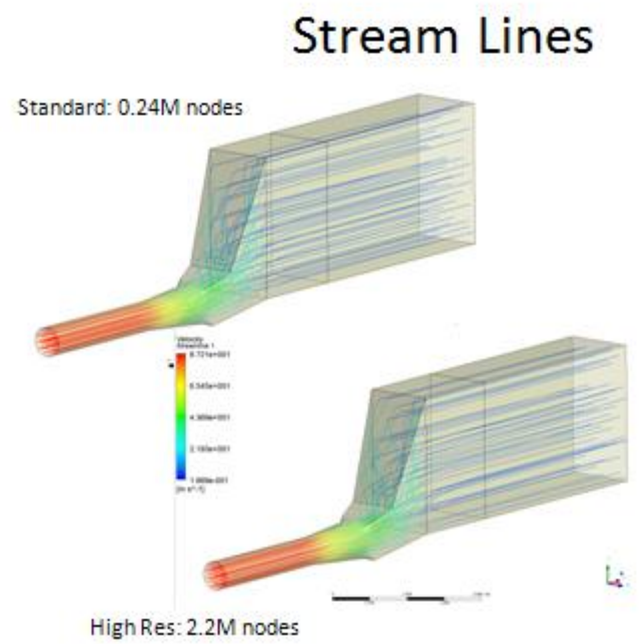


Figure A4c:- Grid sensitivity results (Velocity vectors).

Results.

Streamlines and velocity contours.

The streamlines are shown below in Figure A5, from which it can be seen that the flow pattern shows decay in the velocity through the transition duct with a resulting velocity of around 20-30 m/s at the entrance to the tube bank in the region shown in Figure A4b. The tube bank has the desired effect of unifying the flow downstream from it to a value of around 6-7 m/s



.

Figure A5:- Streamlines illustrating the flow pattern through the HRSG (Open ended).

The CFD predictions of the velocity contours along the central plane are shown in Figures A6a &d for the open topped case. Comparisons with Figure A4a show that there is virtually no difference within the transition section and immediately downstream of the HRSG tube bank between these and the open ended case. This is also apparent from the direct comparisons shown in Figures A6b & c. The latter illustrates the recirculation zone in the upper region of the transition section, which is a known feature of this type of

HRSG design. The flow contours shown in Figure A6d compare favourably with those expected for this type of HRSG design, cf Figure 2.

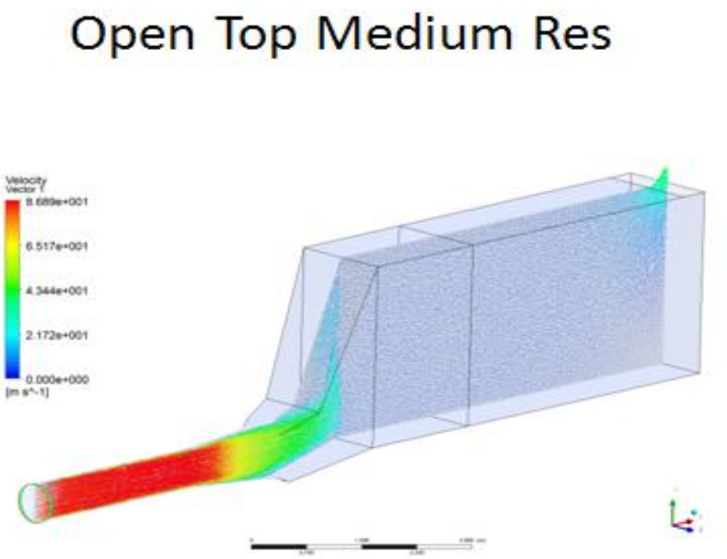


Figure A6a:- Velocity contours through the HRSG with the end sealed and an open top (central plane).

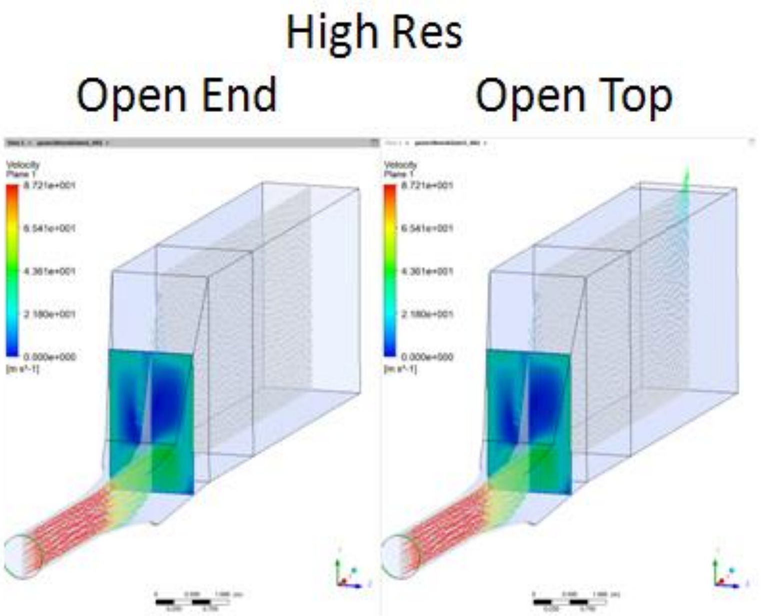


Figure A6b:- Velocity contours through the HRSG for open end and open topped cases (central plane).

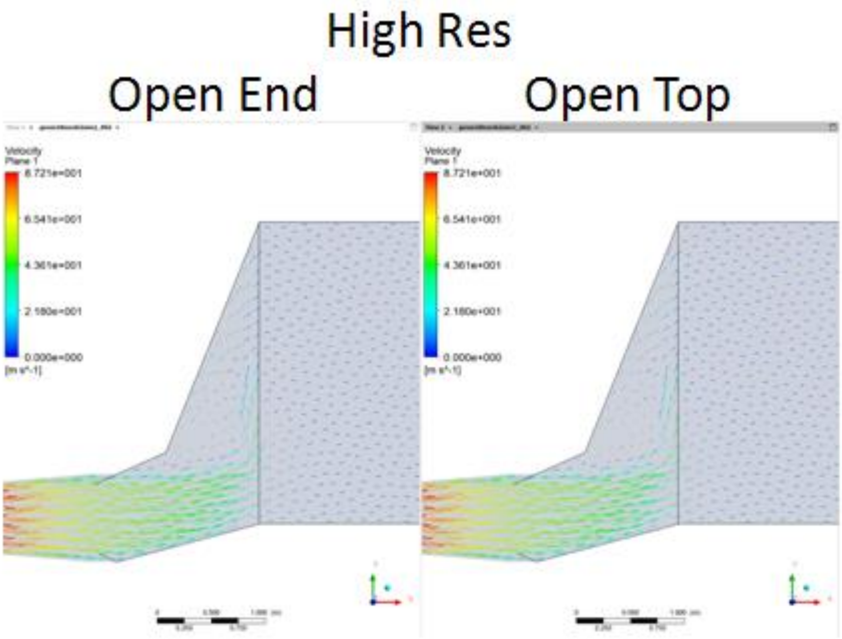


Figure A6c:- Side on view showing velocity vectors along the central plane for both the open end and open topped cases.

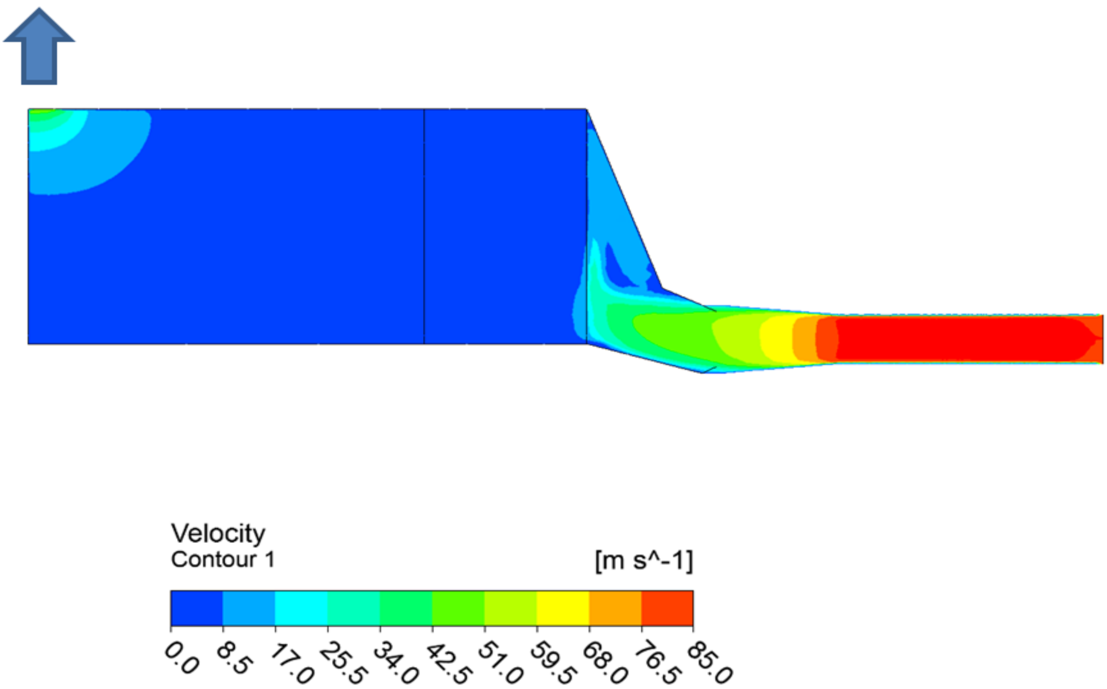


Figure A6d:- Side on view showing velocity contours along the central plane for the open topped case.

Effect of heat exchanger porosity.

The effect of heat exchanger porosity was examined by varying the pressure drop across the tube bundle as shown if Figure A7 below. The results show that the flow patterns are relatively insensitive to significant changes in the pressure drop across the tube bank. The assumed value of 790 Pa was taken from information supplied by GE as typical of the pressuredrop across the type of HRSG being modelled.

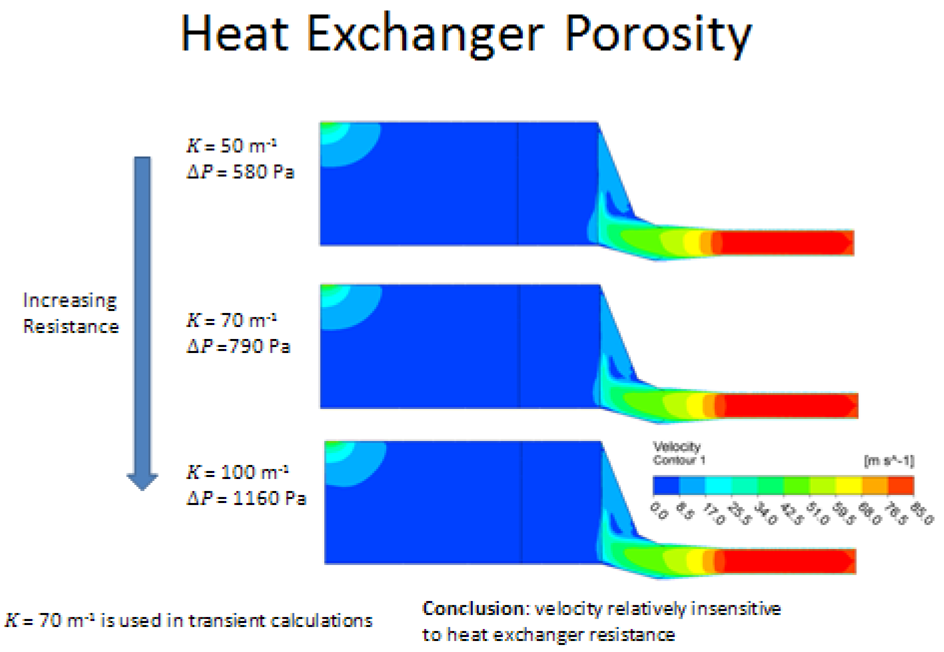


Figure A7:- Influence of assumed heat exchanger porosity (Pressure drop).

Effect of outlet design (Vertical flue or horizontal exit).

The effect of the outlet design on the flow patterns through the HRSG were examined from predictions of the central plane flows for both cases as shown in Figure A8 below. It can be seen that there is no discernible difference between the two, thus showing that the outlet has no effect on the upstream flow distribution probably as a consequence of the dominant pressure drop across the tube bank.

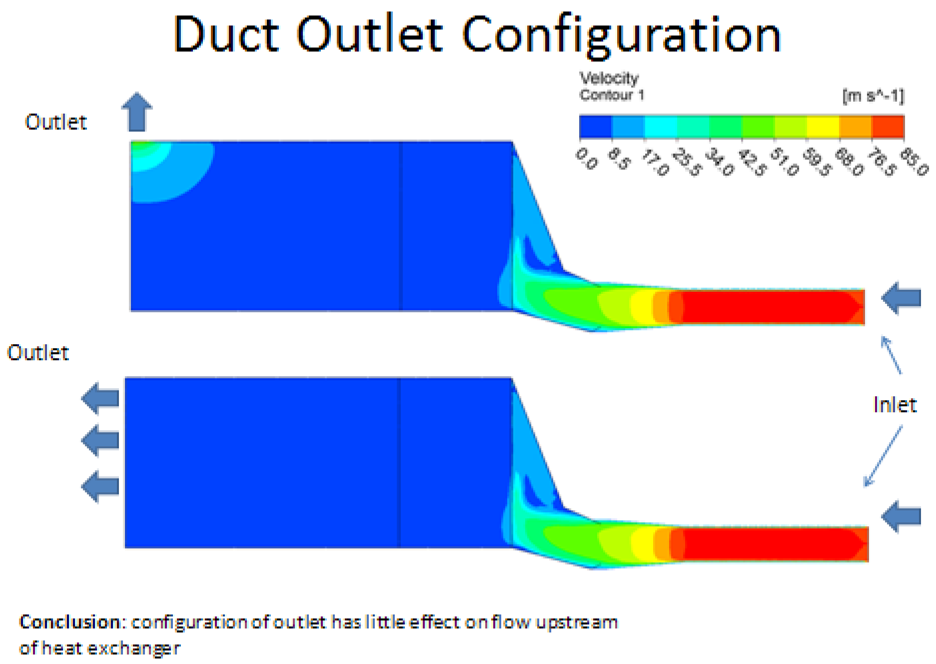


Figure A8:- Velocity contours for the flows through the HRSG with different outlets.

Time – varying gas concentrations.

The build-up in gas concentration within the HRSG as a function of time was examined through a time varying simulation, starting from the case of the HRSG being full of engine only exhaust gas and to which a 15% hydrogen 85% air mixture was suddenly injected at the beginning of the CFD domain. Its progress through the HRSG is shown in Figure A9 a & b below for both the open end and open topped conditions. It can be seen that within three seconds the whole of the HRSG is full of the injected mixture. This being the time that needs to be allowed before an ignition is initiated once the steady gas mixture and oxygen injection conditions have been reached.

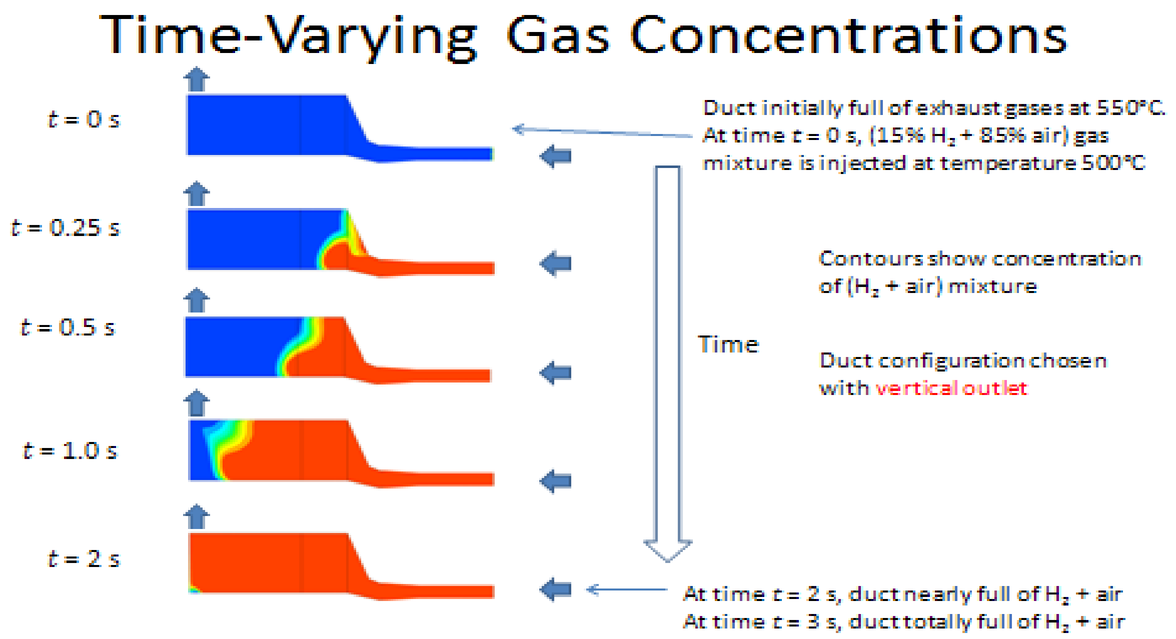


Figure A9a:- Time varying gas concentrations for the open topped case.

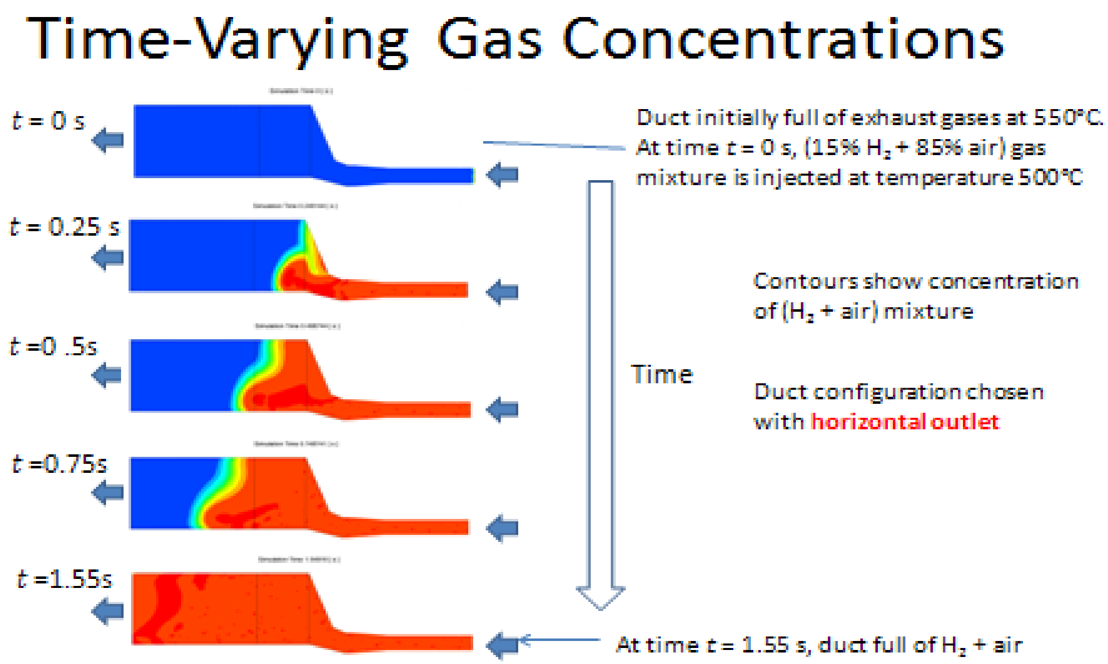


Figure A9b:- Time varying gas concentrations for the open ended case.

Appendix 6:- Gas turbine mass flow calculations

Define the following variables :

mex	=	mass flowrate of exhaust.	-	specify this
Mex	=	molecular weight of exhaust	-	calculated
Mf	=	molecular weight of fuel	-	calculated
FCO	=	mole fraction of CO in fuel mixture	-	specify this
FH2	=	mole fraction of H2 in fuel mixture	-	specify this
FCH4	=	mole fraction of CH4 in fuel mixture	-	specify this
Ff	=	mole fraction of fuel in exhaust	-	specify this
FEXO2	=	mole fraction of oxygen in exhaust	-	given as 0.15718
mO2	=	mass flowrate of additional oxygen		
MO2	=	molecular weight of oxygen		
mf	=	mass flowrate of fuel		
mex/Mex	=	molar flowrate of exhaust		
mf/Mf	=	molar flowrate of fuel		

Additional oxygen molar flow rate required to bring concentration in exhaust up to 0.21 mole fraction is calculated from :

0.21 = (oxygen from exhaust + additional oxygen)/(exhaust + oxygen)

$$0.21 = (F_{EXO2}\, m_{ex}/M_{ex} + m_{O2}/M_{O2}) / (m_{ex}/M_{ex} + m_{O2}/M_{O2})$$

Rearrange to give (1) :

$$m_{O2} = (m_{ex}/M_{ex}\,(0.21 - F_{EXO2})) / (1 - 0.21)$$

Mole fraction of fuel in exhaust calculated from the flowrates of fuel and modified exhaust flow:

$$F_f = (m_f/M_f) / (m_{ex}/(M_{ex} + m_{O2}/M_{O2} + m_f/M_f)$$

Rearrange to give (2):-

$$m_f = (M_f\ F_f)\,(m_{ex}/M_{ex} + m_{O2}/M_{O2}) / (1-F_f)$$

Equations 1 and 2 are mass flow rates of additional oxygen and fuel - calculated by spreadsheet.

Calculation of temperature reduction due to injection of oxygen and fuel mixture.

The reduction in exhaust gas temperature is estimated to be 96 deg.C from a set point of 500 deg.C this is calculated as follows :- Using the following specific heat values; Cp air = 1.005, Cp hydrogen = 14.3. Cp oxygen = 0.91. Maximum mass flow rates are hydrogen 0.2 kg/s, oxygen 1.12 kg/s and combustion products (air) 15 kg/s. Injection temperature is 20 deg.C.

Thus:- 14.3x0.2x(y-20) + 0.91x1.12x(y-20) = 1.005x15x(500-y). Where y is the new temperature after injecting fuel and oxygen. Thus x = 404 deg.C.

This assumes that the gases are injected at an ambient temperature of 20^0 C.