

# **Start-up of the Three-shaft Closed Loop Brayton Cycle Model of the PBMR Power Plant**

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*Abstract – The Pebble Bed Modular Reactor (PBMR) is currently being developed by the South African utility ESKOM, as a new generation nuclear power plant. This so-called high temperature gas-cooled reactor plant is based on a three-shaft, closed-loop, recuperative, inter-cooled Brayton cycle with Helium as the working fluid. In order to demonstrate the envisaged PBMR control methodologies, a model of the plant was built. The conceptual design of the plant was done with the aid of Flownet, a thermal-fluid simulation software package that has the ability to simulate the steady-state and transient operation of the integrated system. This paper describes the differences and similarities between the so-called Pebble Bed Micro Model (PBMM) and the actual PBMR. It provides the layout and overall specifications of the plant and describes the approach followed in the design of the start-up system. It gives the results of the actual start-up event including a comparison between the measured and simulated conditions.*

## I. INTRODUCTION

The Pebble Bed Modular Reactor (PBMR) concept is currently being developed in South Africa as a new generation nuclear power plant. This so-called high temperature gas cooled reactor plant is based on a three-shaft, closed-loop, recuperative, inter-cooled Brayton cycle with Helium as coolant.

In order to demonstrate the operation of this particular closed-loop configuration as well as to illustrate the envisaged PBMR control methodologies for start-up, load following, steady state full load and load rejection, a model of the plant was built by the Faculty of Engineering at the Potchefstroom University for CHE. This so-called Pebble Bed Micro Model (PBMM) was not intended to be an exact scaled-down version of the actual PBMR plant, but the plant layout has the same topology and representative major components. Also, the control system has the same topology and degrees of freedom as that of the PBMR plant.

The design of the plant<sup>1</sup> was done with the aid of Flownet<sup>2</sup>, a thermal-fluid simulation software package that has the ability to simulate the steady-state and transient operation of the integrated system, making use of the performance characteristics of the individual components. The plant was designed, constructed and commissioned within nine-months from January to September 2002.

This paper describes the differences and similarities between the so-called Pebble Bed Micro Model (PBMM) and the actual PBMR. It provides the layout and overall specifications of the plant and describes the approach followed in the design of the start-up system. It gives the results of the actual start-up event including a comparison between the measured and simulated 'bootstrap' conditions. Detail comparisons will only be made once the instrumentation has been properly calibrated. That is part of a verification and validation process that is planned for 2003.

## II. PLANT LAYOUT

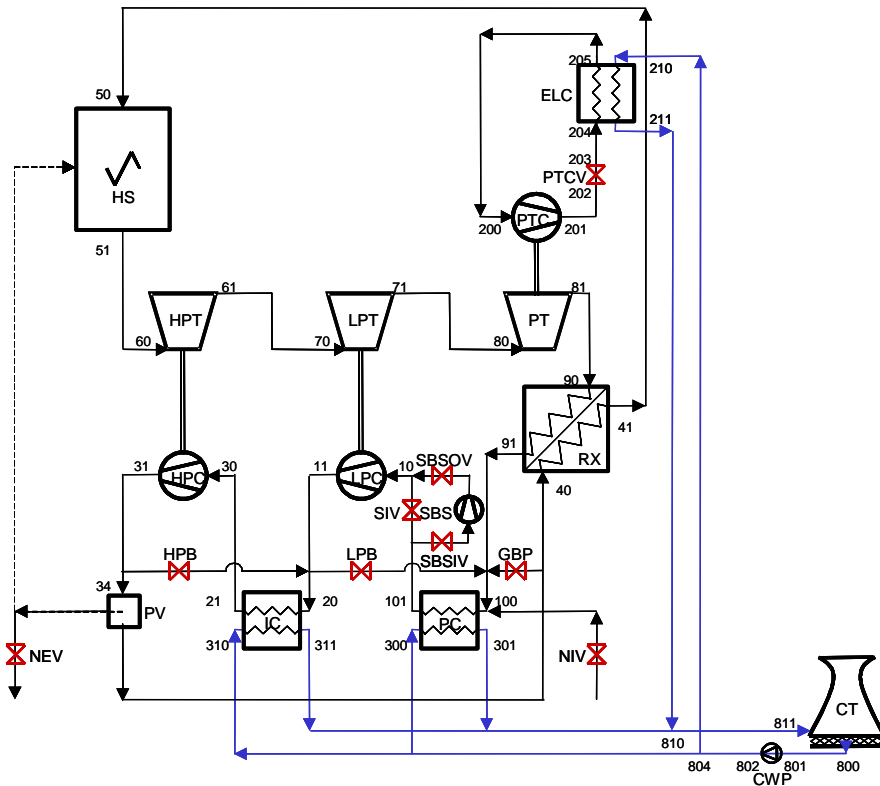
Some of the differences between the model and the actual PBMR plant are as follows:

- The turbo machines are off-the-shelf single-stage centrifugal turbochargers rather than purpose designed multi-stage axial flow machines. The plant was designed around these turbochargers because of obvious time and budgetary constraints. Although there are many differences in the detail design of axial and centrifugal flow machines, their overall performance characteristics within a system are essentially the same with regard to pressure ratio and isentropic efficiency

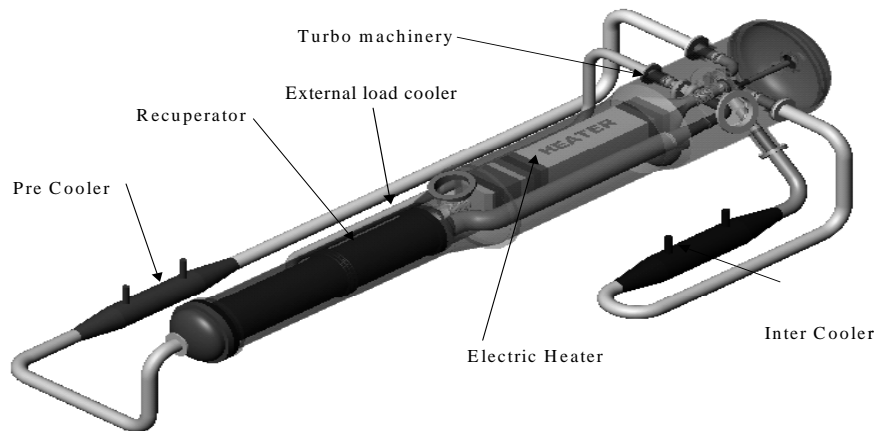
versus non-dimensional mass flow rate. Therefore, it is sufficient to illustrate the overall operation of the cycle.

- The heat source is a high temperature electrical resistance heater of 420kW instead of the pebble bed nuclear reactor. The maximum design outlet temperature of the heater is 700°C.
- The working fluid of the model is nitrogen rather than helium. The main reason for this is to allow the use of off-the-shelf turbochargers that were developed for use in large internal combustion engines with air as working fluid. Nitrogen was chosen instead of air because it has essentially the same thermo-physical properties but contains no oxygen. This is desirable since the presence of oxygen in the cycle may cause corrosion and flammability problems.
- The load on the power turbine shaft is an external load compressor rather than an electrical generator as is the case in the PBMR plant. The energy imparted to the fluid by the compressor is dissipated via an external load cooler.

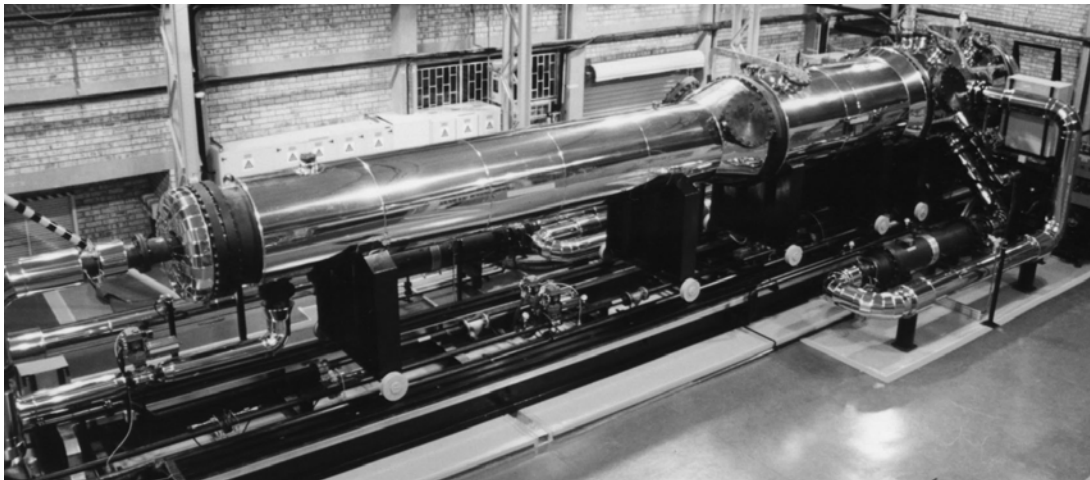
Figure 1 shows a schematic layout of the PBMM plant while Figure 2 shows a solid model drawing and Figure 3 a photograph of the plant. All three turbo-chargers, the heater and the recuperator are situated inside a cylindrical pressure vessel while the pre-cooler, inter-cooler and external load cooler are situated outside of the vessel. The total length of the pressure vessel is 17m.



*Figure 1 Schematic layout of the PBMM plant.*



*Figure 2 Solid model drawing of the physical layout of the PBMM plant.*



*Figure 3 Photograph of the actual PBMM plant.*

The major components in the cycle are (see Figure 1):

- LPC Low pressure compressor.
- IC Inter-cooler.
- HPC High pressure compressor.
- PV Pressure vessel.

- RX        Recuperator.
- HS        Heater.
- HPT      High pressure turbine.
- LPT      Low pressure turbine.
- PT        Power turbine.
- PTC      Power turbine compressor.
- ELC      External load cooler.
- CT        Cooling tower.
- CWP      Cooling water pump.
- SBS      Start-up blower system.
- PV        Pressure vessel.

The following major valves also form part of the system:

- GBP      Gas cycle by-pass valve.
- LBP      LP compressor by-pass valve.
- HBP      HP compressor by-pass valve.
- NIV      NICS injection valve.
- NEV      NICS extraction valve.
- SIV      System in-line valve.
- SBSIV    Start-up blower system inlet valve.
- SBSOV    Start-up blower system outlet valve.
- PTCV     Power turbine compressor valve.

### III. DESIGN OF START-UP SYSTEM

In a three-shaft Brayton cycle, the speeds of the turbo units are not determined by the generator speed. They can therefore run at higher speeds leading to a reduction in size. Maintenance is also simplified because the units are separate. However, the start-up of the three-shaft Brayton cycle presents unique problems because the generator can not be used to turn a compressor to circulate the gas.

In this design, an external blower - the SBS - is used to circulate the gas through the system during start-up. The SBS cannot be exposed to the high temperatures downstream of the heater and is therefore situated downstream of the pre-cooler. The start-up sequence proceeds as follows: The SIV is closed and the SBS is started. Then the heater is switched on to increase the temperature of the gas flowing to the turbines. As the system heats up, the temperature of the nitrogen flowing to the heater increases, which causes the outlet temperature of the heater and the shaft work delivered by the turbines to increase. This enables the compressors to contribute to the power required to circulate the gas and the pressure increase across the SIV (and SBS) drops. The cycle moves towards self-sustained circulation and the SBS is disengaged when the pressure increase over the SIV becomes negative. The cycle is said to have bootstrapped.

The size of the SBS was determined by means of the thermal-fluid network code Flownet. The pressure increase across the SBS was determined as a function of heater outlet temperature for different mass flow rates. From figure 4 it can be seen that the mass flow rate does not have a significant effect on the bootstrap temperature. The bootstrap temperature is also well within the maximum allowable temperature for the HPT. The pressure increase exhibits a maximum pressure difference at low heater outlet temperatures and the maximum pressure difference increases with mass flow. For any given mass flow, the peak determines the size of the SBS. The question that now needs to be answered is how to determine the mass flow rate.

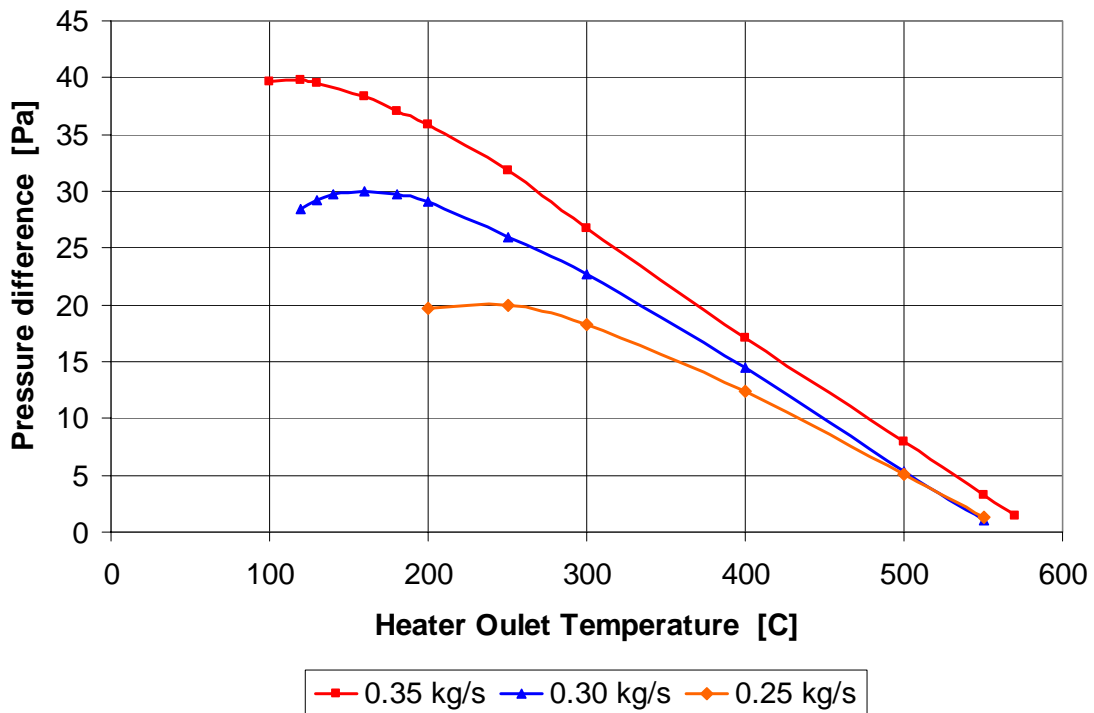


Figure 4 Pressure increase over the SBS for different mass flow rates during start-up

It would seem that a blower with a low mass flow rate would be sufficient. However, a positive displacement blower with low mass flow rate may cause the compressors to run into surge. This happens because, for a positive displacement blower, the non-dimensional mass flow rate does not change much with a change in pressure ratio. With a low mass flow rate the operating point lies to the left on the x-axis of the compressor characteristic curve shown in figure 6. As the system heats up, this point moves almost vertically upwards because the SBS keeps the flow rate almost constant even though the compressors start to contribute towards the pressure increase. With a too small mass flow rate, the operating point can approach and reach the surge line. Therefore, a blower with a mass flow rate of 0.3kg/s was selected. This is rather high, but it was decided to be on the safe side. The map of the SBS is shown in figure 5. The x-axis is the non-dimensional flow rate relative to the non-dimensional flow rate at the actual bootstrap point.

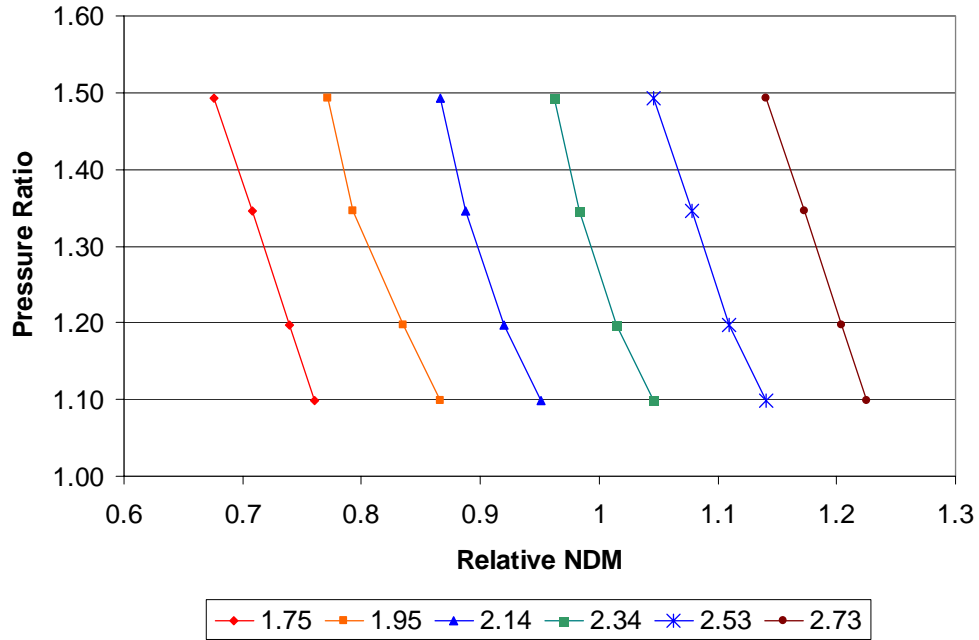


Figure 5 Pressure ratio as function of non-dimensional mass flow for the SBS at different non-dimensional speeds

### III.A. Start-up results

The trace of the operating point on the low-pressure compressor map during start-up is shown in figure 6. On the x-axis the non-dimensional mass flow rate (relative to the non-dimensional mass flow rate at the bootstrap point) is shown. The different curves on the map are the different non-dimensional speed curves.



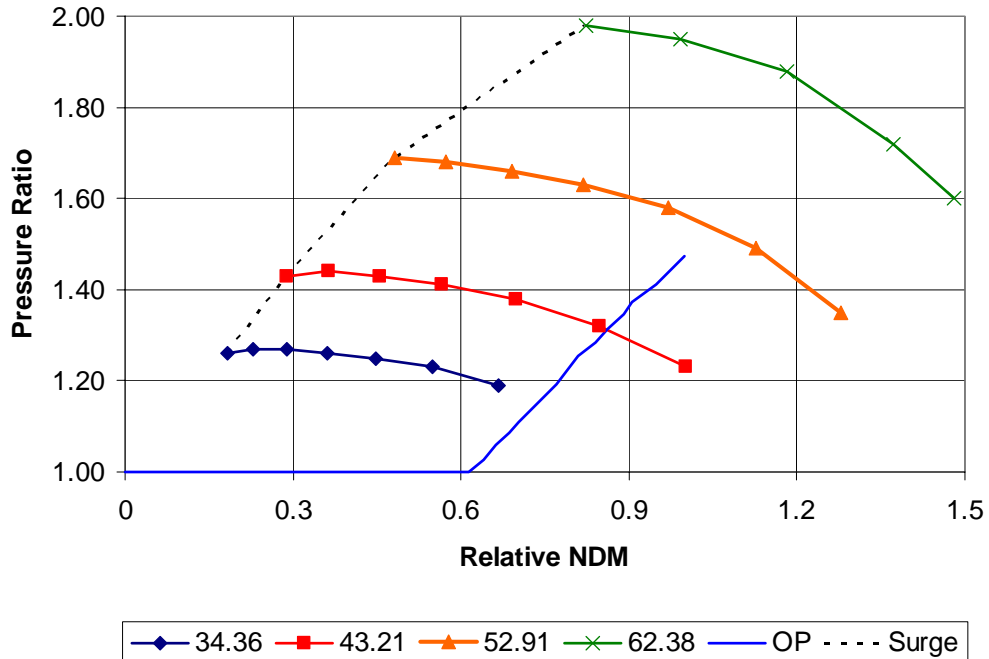
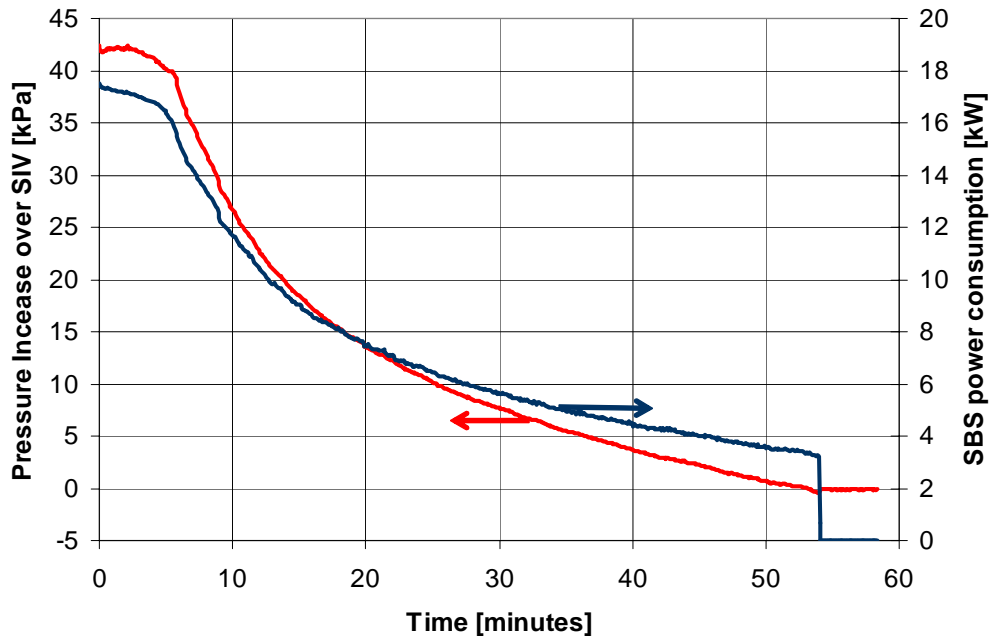


Figure 6 Trace of the operating point (OP) on the LPC compressor map during start-up.

It can be seen that the operating point is at all times during start-up well clear of the surge line. The trace is not vertical because a decrease in the value of the pressure term in the denominator of the non-dimensional mass flow rate term causes its value to increase. If a centrifugal compressor were used, a pressure ratio would be set up at lower flow rates and the trace will run closer to the surge line.

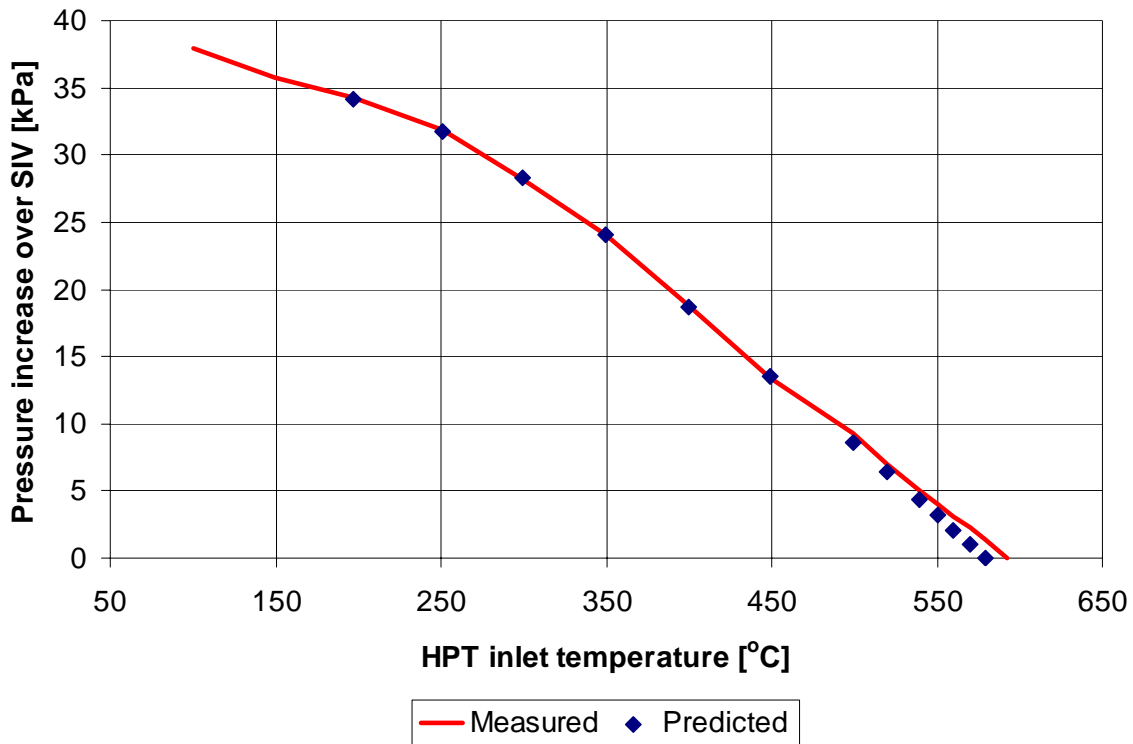
For start-up, the power to the heater is kept constant at about 180kW. From the graphs in figure 7 it can be seen how the power consumption of the SBS decreases as the compressors start to contribute to the power required to circulate the gas. Initially there is a high pressure increase across the (closed) SIV. This decreases slowly and the moment it reaches -0.5kPa, the SIV opens and the SBS is disengaged as can be seen by the sudden drop to zero of the SBS power consumption curve.



*Figure 7 Pressure increase over the SIV and the SBS power consumption as function of time*

The exit temperature of the heater is probably the most important determinant of the bootstrap point as the energy that the turbines can deliver, depends on the gas inlet temperature. An estimation of the bootstrap temperature was made by calculating (with Flownet), the steady-state pressure increase over the SIV as function of heater outlet temperature. In Figure 8 a comparison between the calculated and measured variables can be seen. The agreement between the measured pressure drop and the calculated pressure drop is quite good, especially at lower heater outlet temperatures. The actual bootstrap temperature is 592°C while the calculated temperature is 579°C.

It should be kept in mind that it is a comparison between a calculations done at steady-state while start-up is a transient condition. A more valid comparison will only be possible once the integrity of the measurements has been confirmed during the verification and validation study that will be conducted in 2003.



*Figure 8 Measured and predicted pressure difference across the SIV as function of heater outlet temperature.*

#### IV. CONCLUSIONS

a) An effective start-up system for a three shaft Brayton cycle was designed, built and implemented. To date the plant has been started up more than twenty times. The plant starts up smoothly and the transition through the bootstrap point to self sustained operation is smooth. This effective design was made possible by the ability to simulate the start-up sequence by making use of the Flownet software.

b) The methodology developed during the design of the start-up system can also be used for the start-up of other configurations making use of external means for circulating the gas during start-up. This will make possible the construction of cost-effective systems with off-the-shelf components. Such systems can be used for the supply of compressed air or by adding an air-standard refrigeration cycle - the provision of refrigeration capacity without the need for large amounts of electricity.

c) The agreement between the first measured values and the simulated values are good, but detailed comparisons will only be possible during the validation and verification phase the will take place during 2003.

#### REFERENCES

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