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COMPARISON OF THE THERMAL-FLUID ANALYSIS CODE FLOWNEX WITH EXPERIMENTAL DATA FROM THE PEBBLE BED MICRO MODEL

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ABSTRACT

In this paper a comparison of the thermal-fluid analysis code Flownex with experimental data from the Pebble Bed Micro Model (PBMM) is presented. From the measured data it became clear that there were substantial heat losses from the turbines and the associated support structure as well as from the pressure vessel to the ambient. The original Flownex model was improved to account for these heat transfers. The new Flownex model was then used to simulate a mass injection transient test done on the PBMM.

In order to do proper simulation it is necessary to understand and quantify all the processes taking place in the plant. This is difficult when complex geometries are being modeled and when components are installed in different conditions than the conditions under which they were tested and characterized. Keeping these limitations in mind, good agreement between the experimental and simulation results was obtained.

INTRODUCTION

The design and analysis of fluid flow and heat transfer in complex closed-loop systems like nuclear reactors require the use of a variety of analysis techniques and simulation tools. These range from one-dimensional pipe network codes, to very advanced three-dimensional CFD codes. Three-dimensional CFD codes are useful for accurate geometrical and physical modeling of individual system components, but are not practical for analyzing complete integrated systems due to the excessive computational resources required and the time it takes to solve. While one-dimensional tools cannot resolve the detail flow field within components, they allow efficient analysis of complete systems. After careful validation and stringent qualification procedures, one-dimensional codes are used to analyze the behavior of nuclear power plants in both normal operation and various accident scenarios.

This paper presents a comparison of the one-dimensional systems CFD code Flownex [1]with experimental data from the PBMR Micro Model.

The PBMR Micro Model is currently subject to an international benchmark for simulation codes in the coordinated research program (CRP-5), under the auspices of the IAEA. A comparison between Flownex and the French code CATHARE is part of this program and results has been presented at HEFAT 2005 [2].

DESCRIPTION OF THE SIMULATION CODE

A systems CFD code, called Flownex [4], has been developed by M-Tech Industrial in association with the Pebble Bed Modular Reactor company that enables users to perform detailed analysis and design of complex thermal-fluid systems such as complete power plants and thermal-fluid networks.

Similar to a conventional CFD code, the system is discretized into a number of spatial or conceptual control volumes to which a set of conservation equations are applied and then solved. Although the term CFD is usually reserved for 3-D Navier Stokes solvers, Flownex does not solve the 3-D Navier Stokes equations, but a set of simplified 1-D momentum equations applied to 3-D spatial control volumes. This approach is valid for flow through a porous medium and is exactly the same approach used in classical CFD codes.

Since Flownex solves porous flow in 3-D spatial volumes in the same way as classical CFD codes and in addition to that also the balance of plant, the name systems CFD or SCFD for short, is a fitting description.

The Flownex solver is based on an implicit Newton solver that solves the momentum equation in each element and the continuity and energy equation at each node in large arbitrarily structured networks for both steady-state and dynamic situations. This gives Flownex a pseudo CFD capability, which allows it to predict complex phenomena such as pressure and temperature waves in pipes and buoyancy effects in packed beds. The solver is optimized for steady-state and transient flows and can deal with both fast and slow transients.

Although components may be represented on a systems level as a single entity they may in fact be complex sub-networks. The nuclear reactor and heat exchangers are not treated as lumped systems but as distributed systems_the nodalization of which can be used defined. Flownex features two nuclear reactor simulation models that combine point kinetic neutronics with detailed two-dimensional finite difference thermal-fluid models. The model deals with feedback from isotope changes and therefore calculate reactivity changes due to changes in the Xe concentration. The code can also deal with one, two or three dimensional conductive heat transfer through solid structures.

In order to ensure the accuracy of Flownex a rigorous verification and validation (V&V) process has been implemented [3] to guarantee the integrity of engineering analyses and to satisfy statutory requirements regarding the licensing and operating of nuclear plants in South Africa and abroad.

THE PEBBLE BED MICRO MODEL (PBMM)

A solid model of the PBMM is shown in Figure 1 with a schematic layout of the PBMM power conversion cycle shown in Figure 2. The length of the pressure vessel is 17m and the electric heat source has a rating of 420kW. Starting at 1 (in Figure 2), nitrogen at a relatively low pressure and temperature is compressed by a low-pressure compressor (LPC) to an intermediate pressure 2 where after it is cooled in an intercooler (IC) to state 3. A high-pressure compressor (HPC) then compresses the nitrogen to state 4. From 5 to 6 the nitrogen is preheated in the recuperator (RX) before entering the electric resistance heater (HS), which heats the nitrogen to state 8. After the electric heater the hot, high-pressure nitrogen is expanded in a high-pressure turbine (HPT) to state 9 after which it is further expanded in a low-pressure turbine (LPT) to state 11. The high-pressure turbine drives the high-pressure compressor while the low-pressure turbine drives the low-pressure compressor. After the low pressure turbine the nitrogen is further expanded in the power turbine (PT) to pressure 13. From 13 to 14 the still hot nitrogen is cooled in the recuperator after which it is further cooled in the pre-cooler (PC) to state 1. This completes the cycle. The heat rejected from 13 to 14 is equal to the heat transferred to the nitrogen from 5 to 6.

From 15 to 16 a generator is emulated by an external load compressor (ELC) connected to a power dissipation loop consisting of a flow control valve and a heat exchanger (ELHX) as shown in Figure 2. The pressure level in the load rejection loop is the same as the suction pressure of the LPC.

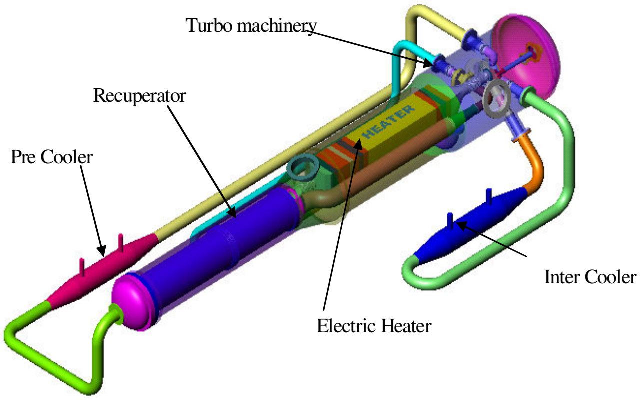

Figure 1: Solid model of the PBMM.

The output of the plant can be controlled by changing the nitrogen inventory of the system or by opening and closing of the bypass valve (BPV). Changing of the nitrogen inventory is a relatively slow process and is used for load following while the faster bypass control is used for load rejection.

The PBMM experimental facility presents great opportunities for code verification and validation (V&V) as it presents a complex thermal-fluid system with various thermal-fluid components such as heat exchangers as well as dynamic components such as turbo machines and control valves. To date a number of steady-state and transient runs have been completed on the PBMM facility.

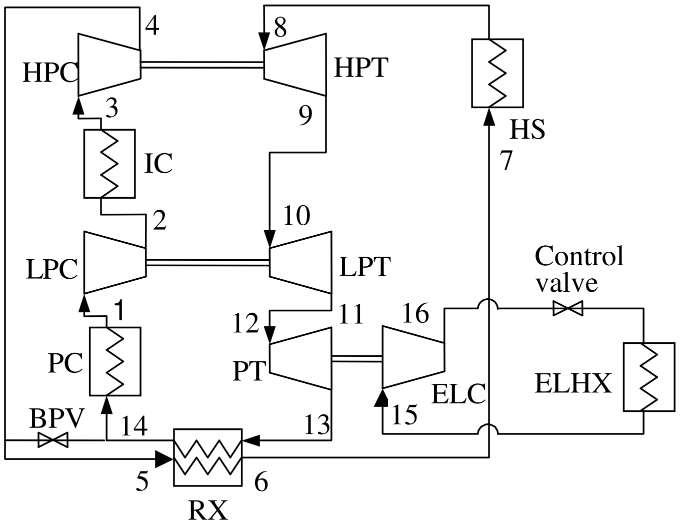

Figure 2: Schematic layout of the PBMM.

Steady-state tests

To obtain a unique, steady-state operating point for the PBMM the heater outlet temperature, the Low Pressure Compressor (LPC) suction pressure, the opening of the valve in the External Load Compressor (ELC) loop and the cooling water (CW) flow rate through each cooler are set. The cooling water temperature is not a controlled variable and varies with ambient conditions and is therefore not controlled and only measured. Two steady-state runs were done. The suction pressure of the LP compressor was set at (nominally) 95 kPa and 115 kPa to give two unique operating conditions. The heater outlet temperature set point was kept at 650°C. The average values obtained in two steady-state runs are shown in table 1.

Table 1: Operating conditions during the two steady-state runs: 95kPa and 115kPa.

Nominal LPC inlet pressure	95kPa	115kPa
Suction pressure of LPC [kPa(a)]	94	113.5
Heater outlet temperature [°C]	647.7	649.7
CW flow rate PC [kg/s]	2.05	
CW flow rate IC [kg/s]	1.63	
CW flow rate ELHX [kg/s]	1.2	
CW temperature[°C]	14.2	
CW pressure [kPa(a)]	350	
Nitrogen purity[%]	100	
Valve opening on ELC	Fully open	
Compressor bypass valve	Closed	

Equipment details and the plant configuration are fully described in the PBMR Micro Model Data Pack [1].

When the experimental results of the PBMM were presented on a T-s diagram, it was seen that the collective entropy increase of the gas flowing through the turbines is less than expected. This can possibly be attributed to the following reasons:

a) Significant heat loss from the turbines
b) Low temperature gas leaking into the pipe work connecting the turbines
c) Measurement error

Much work was done to determine which of the three possible reasons was the most likely. Measurement error will always be present to some extent but finally it was decided that the most probable reason was that significant heat loss is taking place from the turbines. It is possible to calculate the magnitude of the heat loss from the turbines as well as the heat loss from the pressure vessel to the ambient from the experimental results. These heat losses were not included in the first Flownex model of the PBMM. There are two reasons for this:

a) It was thought that the heat losses will only be of secondary importance.
b) The heat losses take place from complex, undefined geometries and it would have been very difficult if not impossible to build models for the heat transfer paths.

Therefore experimental results had to be used to establish the importance and quantify the heat losses. Generic heat transfer paths were then included in the simulation model and the heat transfer coefficients adjusted until good comparison between the experimental and simulated values were obtained.

Transient tests

In order to build confidence in Flownex it is necessary to test its ability to predict behavior under new operating conditions. Two possibilities for this exist:

a) The heat loss to the ambient can be reduced significantly and the ability of Flownex evaluated to predict the value of process variables under the new condition. This activity is planned for the second half of 2006.
b) Perform transient tests and compare the results.

Various transient tests on the PBMM have been identified. These include load following, load rejection and start-up. In this paper the focus will be on nitrogen injection. Nitrogen is injected into the cycle just upstream of the Pre-Cooler in order to increase the inventory of nitrogen in the cycle. As the mass of nitrogen in the cycle increases, the power output of the power turbine also increases. Before injection commences, the plant is run at steady-state (as in Table 1) with a LPC suction pressure of 95kPa. Nitrogen is now injected into the cycle at a rate of 0.0227kg/s for about a minute. The set point of the heater outlet temperature remains the same.

RESULTS

Steady-state – 95kPa LPC suction pressure

Table 2 shows the comparison between the measured temperatures (EXP) and the values obtained with Flownex (FNX), with heat transfer included, for the 95 kPa LPC suction pressure case. The absolute value of the percentage difference is also shown. In Flownex the temperature of the high pressure nitrogen entering the recuperator is fixed on the same value as the measured value and the heat gain of the HP nitrogen flowing on the outside of the heater, calculated. This was done because the heat balances showed that the electrical heater was losing heat to the gas on the outside but is was difficult to quantify this heat loss.

The average of the differences is 1 percent. For the 115kPa case the percentages of the differences are similar with an average of 1.2 percent . The biggest differences are at the “hot end” of the recuperator (RXLP Inlet and RXHP outlet). This is because of the measured temperature drop from 697.8K to 689.4K between the Power Turbine outlet and the Recuperator inlet. This was not modeled in Flownex with a Heat Transfer Path as the difference between the measured and simulated temperatures are not excessive - less than 5 percent. The effect is however that the hot end of the recuperator in Flownex has a higher temperature than the actual plant.

Table 3 shows the comparison between the measured pressures (EXP) and the values obtained with Flownex (FNX). The absolute value of the percentage difference is also shown.

Table 2: Steady-state (95 kPa) – Temperature comparison

Position	Temperature [K]		Difference [%]
	EXP	FNX	
PC Inlet	449.2	444.2	1.1
PC Outlet	291.3	290.2	0.4
LPC Inlet	293.8	290.2	1.2
LPC Outlet	359.7	356.2	1.0
IC Inlet	359.7	356.2	1.0
IC Outlet	290.0	289.1	0.3
HPC Inlet	289.8	289.1	0.2
HPC Outlet	360.7	357.4	0.9
RXHP Inlet	403.4	403.5	0.0
RXHP Outlet	643.1	664.5	3.3
Heater outlet	920.9	920.9	0.0
HPT Inlet	920.9	920.9	0.0
HPT Outlet	818.2	834.5	2.0
LPT Outlet	748.2	753.1	0.7
PT Inlet	748.7	753.1	0.6
PT Outlet	697.8	703.7	0.9
RXLP Inlet	689.4	703.7	2.1
RXLP Outlet	452.0	444.2	1.7

Table 2: Steady-state (95 kPa) - Pressure comparison

Position	Pressure [kPa(a)]		Difference [%]
	EXP	FNX	
PC Inlet	94.0	94.0	0.0
PC Outlet	92.7	93.7	1.1
LPC Inlet	94.0	92.4	1.7
LPC Outlet	155.8	162.2	4.1
IC Inlet	159.4	160.9	0.9
IC Outlet	159.1	160.6	1.0
HPC Inlet	159.5	160.4	0.6
HPC Outlet	291.5	287.3	1.4
RXHP Inlet	286.6	286.4	0.1
RXHP Outlet	286.4	284.8	0.5
Heater outlet	286.9	284.4	0.9
HPT Inlet	286.9	284.4	0.9
HPT Outlet	202.0	189.3	6.3
LPT Inlet	195.4	189.3	3.2
LPT Outlet	123.2	122.9	0.3
PT Inlet	125.2	122.9	1.8
PT Outlet	96.0	95.4	0.6
RXLP Inlet	92.6	94.8	2.4
RXLP Outlet	94.1	94.3	0.2

The average of the differences is 1.5 percent. For the 115kPa case the percentages of the differences are similar with an average of 1.4 percent.

Table 3 shows the correspondence between the measured and simulated turbine speeds and mass flow rates. For the 115kPa case the correspondence is similar.

Table 3: Steady-state (95kPa) Mass flow rate and turbine speed comparison.

	EXP	FNX	Difference
MASS FLOW RATE	[kg/s]		[%]
Brayton cycle	0.449	0.429	4.6
External load compressor	0.529	0.596	12.7
TURBINE SPEED	[rpm]		[%]
HPT speed	66298	64323	3.0
LPT speed	63707	62513	1.9
PT speed	32294	31757	1.7

The correspondence between the values is generally quite good. The biggest difference is in the mass flow rate in the external load loop.

Transient tests: Injection.

For this test, the plant was run under steady-state with a 95kPa LPC suction pressure and 650°C heater outlet temperature. Nitrogen was then injected at a rate of 0.0227 kg/s for 63 seconds at the LPC inlet. Figure 3 shows the measured and simulated suction pressure of the LPC during the injection transient.

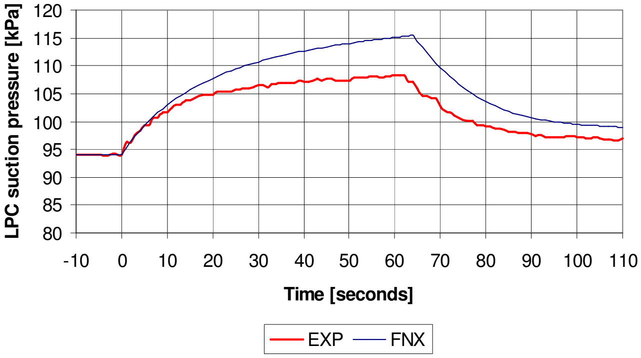

Figure 3: Change in LPC suction pressure.

The simulated value changes by 21.4kPa while the measured value changes by 13.2kPa. This means that the calculated change is 163% of the measured change. Calculated as percentage of the measured value, the difference when injection is stopped, is (115.4-107.2)/107.2=7.7%

Figure 4 shows the measured and simulated speed of the LPC. In order to make a comparison of the relative changes easier, the simulated values are adjusted to give the same initial speed as the measured value. (From table 3 it is clear that at the beginning of the transient, the simulated speed is lower than the measured speed.)

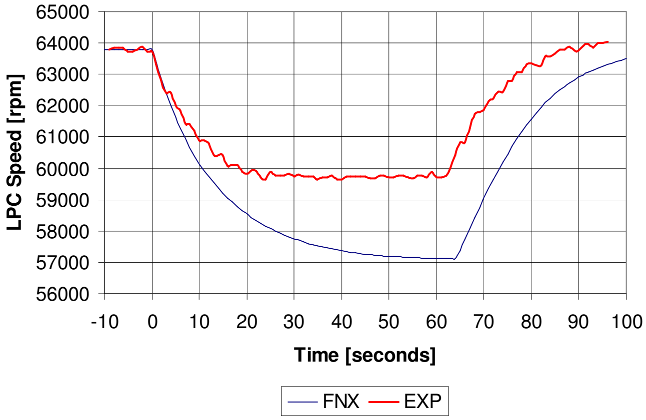

Figure 4: Change in LP compressor speed.

The experimental value changes by 4090rpm and the simulated value by 6674rpm. This means that the calculated change is 163% of the measured change. The difference in the turbine speeds at the end of the injection is (59707-57123)/59707=4.3% The other compressors have similar differences. A summary is given in table 4.

Table 4: Difference in turbine speeds at the end of injection (around 63 seconds)

	ΔSimulated/ ΔMeasured [%]	Difference [%]
HP Turbine	173	2.8
LP Turbine	163	4.3
Power Turbine	213	7.9

Figure 5 shows the comparison between the measured and simulated pressure in the annulus before the Recuperator HP inlet. The simulated values were adjusted to give the same initial value as the measured value.

The measured value changes by 209kPa and the simulated value by 212kPa. This means the simulated change is 102% of the measured change.

DISCUSSION OF RESULTS

After the addition of the heat transfer paths, the comparison between the simulated and measured data for the steady state is good. It is therefore necessary to test the ability of Flownex to simulate a new operating condition. This will be done in the second half of 2006 when the heat loss to the ambient will be reduced significantly.

For the transient results the agreement between the measured and simulated values are not as good. Most probably this is because the connecting pipe-work between the turbo machines is very short. The flow profile of the gas entering the turbine is therefore not properly developed and the actual characteristics will be different from the characteristics as determined by the supplier.

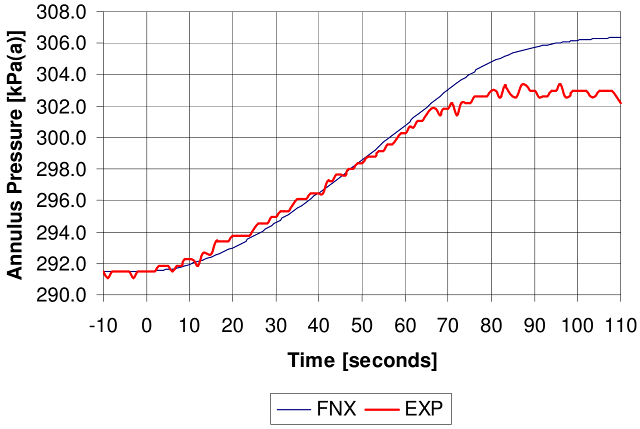

Figure 5: Recuperator high pressure side.

CONCLUSIONS

Flownex has illustrated its ability to simulate a complex, integrated thermal-fluid network. Given the many unknown factors in the PBMM, the agreement between the measured and simulated values are good.

It is not always possible to simulate all processes taking place in a complex fluid network. In the PBMM an example of such a process is the heat transfer from the turbines and the associated support structure to the pressure vessel. The magnitude of the heat transfer had to be determined from experimental results and added to the Flownex model. Such unknown processes will lower the integrity of the results. If the integrity is paramount, unknown factors must be eliminated.

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