PERFORMANCE ANALYSIS OF HELIUM INVENTORY CONTROL OF RGTT200K COOLING SYSTEM

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ABSTRACT

PERFORMANCE ANALYSIS OF HELIUM INVENTORY CONTROL SYSTEM OF RGTT200K COOLING SYSTEM. RGTT200K is a power reactor, designed based on HTGR technology having capability to operate at high temperatures. RGTT200K features are 200 MWth power, helium-cooled, graphite moderator and reflector, pebble fuel type, and uses the Brayton direct cycle. Helium Inventory Control System (HICS) is one of its safety system which maintains the pressure, the helium coolant quality and quantity to meet safety requirements. The HICS consists of 3 subsystems, namely: Inventory Control System (ICS), Helium Purification System (HPS), and Helium Make-Up System (HMS). All of the systems have the function to maintain pressure, helium quality and quantity so that the reactor can operate reliable and safely. This paper discusses the performance of the ICS, which is integrated to the reactor coolant. The research objective was to determine the helium storage tank response rate, when primary coolant is overpressured and depressurized. The methodology used in this research is modeling and simulation by using ChemCAD. In previous research, the HPS, ICS and HMS have been modeled but have not been integrated yet in to the primary coolant. The simulation results showed that the time required for the injection tank back to the coolant normal pressure of 52 bars, due to depressurization up to 5 % was 160 seconds. While the time required for bleeding / blowdown to the storage tanks due to overpressurization up to 5 % was 186 seconds.

Keywords: performance, helium inventory control, primary coolant, RGTT200K

ABSTRAK

ANALISIS KINERJA SISTEM KENDALI INVENTORI HELIUM PADA SISTEM PENDINGIN RGTT200K. *RGTT200K adalah reaktor daya yang dirancang berbasis teknologi HTGR dan mampu beroperasi pada temperatur tinggi. Ciri RGTT200K adalah berdaya 200 MW termal, berpendingin helium, moderator dan reflektor grafit, berbahan bakar pebble, dan konversi energi menggunakan siklus Brayton langsung.. Sistem Kendali Inventori Helium (SKIH) merupakan sistem keselamatan dalam RGTT200K yang berfungsi untuk mempertahankan tekanan, kualitas dan kuantitas helium pada pendingin reaktor sehingga memenuhi persyaratan keselamatan yang ditetapkan. Sistem Kendali Inventori Helium terdiri dari 3 bagian subsistem, yaitu: Sistem Kendali Inventori (SKI), Sistem Pemurnian Helium (SPH), dan Sistem Make-Up Helium (SMH). Ketiga subsistem ini secara simultan mempunyai fungsi untuk mempertahankan tekanan, kualitas dan kuantitas helium pendingin reaktor sehingga reaktor dapat beroperasi secara handal dan aman. Makalah ini membahas kinerja SKIH yang diintegrasikan dengan pendingin RGTT200K. Tujuan penelitian adalah untuk mengetahui kecepatan respon tangki penyimpan helium ketika terjadi keadaan tekanan berlebih (overpressure) dan tekanan berkurang (depressurized) pada pendingin. Metodologi yang digunakan adalah pemodelan dan simulasi dengan perangkat lunak ChemCAD. Pada penelitian sebelumnya telah dilakukan pemodelan SPH, SKI dan SMH tetapi belum diintegrasikan ke sistem pendingin. Hasil simulasi menunjukkan bahwa waktu yang dibutuhkan untuk proses surge (injeksi) tangki untuk kembali ke tekanan operasi normal 52 bar, akibat depressurisasi sampai dengan 5% adalah 160 detik. Sedangkan waktu yang dibutuhkan untuk bleeding/blowdown pendingin ke tangki penyimpanan akibat tekanan berlebih sampai dengan 5% adalah 186 detik.*

Kata kunci *: kinerja, kendali inventori helium, pendingin primer, RGTT200K*

INTRODUCTION

RGTT200K (Reaktor Gas Temperatur Tinggi 200 MW Kogenerasi / Cogeneration High Temperature Gas Reactor 200 MW) is a power reactor which is designed based on HTGR technology having capability to operate at high temperature. It produces 200 MW thermal of power and uses helium gas as coolant, graphite moderator and reflector, pebble fuel with graphite cladding, and energy conversion using the direct Brayton cycle [1].

The main safety system feature of RGTT200K is inherent safety, where the safety system relies on negative coefficient of reactivity. As the reactor temperature increases, the reactor core temperature does not exceed 1600 °C [2, 3]. Related to that, the material structure of the system and reactor core components consisting of graphite will not be damaged or melted during the loss of helium coolant accident as the graphite melting point is 2300 °C.

Water ingress which occurs in the reactor both in normal operating or postulated accident condition will cause aggressive gas impurities in the reactor coolant [4]. The gas impurities would threaten the integrity of the material structure of reactor components that interfere with the safety and reliability of operation. To maintain the safety and reliability of reactor operation, the quality and quantity of impurities in the coolant must be maintained on the limit of safe concentration range [5,6].

RGTT200K is designed with direct cycle, where the cooling system is connected directly from the reactor core to the turbine and generator without using steam generators or heat exchangers. Helium Inventory Control System or HICS is a second safety system which serves to maintain the pressure, the quality and quantity of helium in the reactor coolant so that it meets safety requirements. The Helium Inventory Control System consists of three subsystems, namely: Inventory Control System (ICS), Helium Purification System (HPS), and Helium Make-Up System (HMS) [7,8,9]. All of these subsystems simultaneously maintain the pressure, helium purity so that the reactor can operate reliable and safely.

At normal operation, rotation of turbine blades will result in pressure instability. The instability of this pressure would be anticipated using the Inventory Control System (ICS). To guarantee the amount or quantity of helium gas in the cooling system the Helium Make up System (HMS) is designed. If there is a daily leakage then the HMS will inject pure helium gas from the fresh helium storage tanks. While the quality or purity helium will be guaranteed by the Helium Purification System (HPS). This system will purify solid particles or carbon dust and other gases impurities formed inside the coolant. Pure helium gas that has been purified will be stored in a storage tank and some will be recycled back into the primary cooling system [10].

This paper discusses the performance of the ICS integrated to the primary coolant of RGTT200K. The research objective was to determine the response speed of the helium storage tank during overpressurization and depressurization condition of the primary cooling system. The methodology used is by modeling and simulation of the ICS using ChemCAD software. In the previous research, the HPS modelling has been done but did not integrated yet into the primary coolant. By knowing the storage tanks response time against overpressurization and depressurization conditions, the pressure transient condition will be expected on the primary coolant system. Transient conditions can be used to anticipate the maximum or minimum temperature alteration.

THEORY

Inventory Control System

The Inventory Control System (ICS) has two main functions, which are controlling the pressure of primary coolant and providing helium in the storage tanks with 4.5 MPa up to 7.28 MPa of pressure and one booster tank with 9.0 MPa pressure. The primary coolant system pressure control is achieved using the principle of pressure difference or pressure ratio between RGTT200K cooling system and storage tanks [11]. The pressure control philosophy especially for storage tanks is performed using a compressor. This compressor works to raise the helium pressure so that can be stored in a storage tank. The ICS conceptual design is shown in Figure 1. Components of the ICS are: storage tanks, control valves, mass capacitance, isolation valves, pressure relief valves, bursting disc, the main compressor, multipurpose compressor, piping, and buffer tanks [12].

Helium Make-up System

The Helium Make-Up System (HMS) has the main function to supply additional fresh helium into storage tanks to compensate the daily leakage. The helium amount or quantity in the primary coolant should be maintained in fix value so that leaked gas can

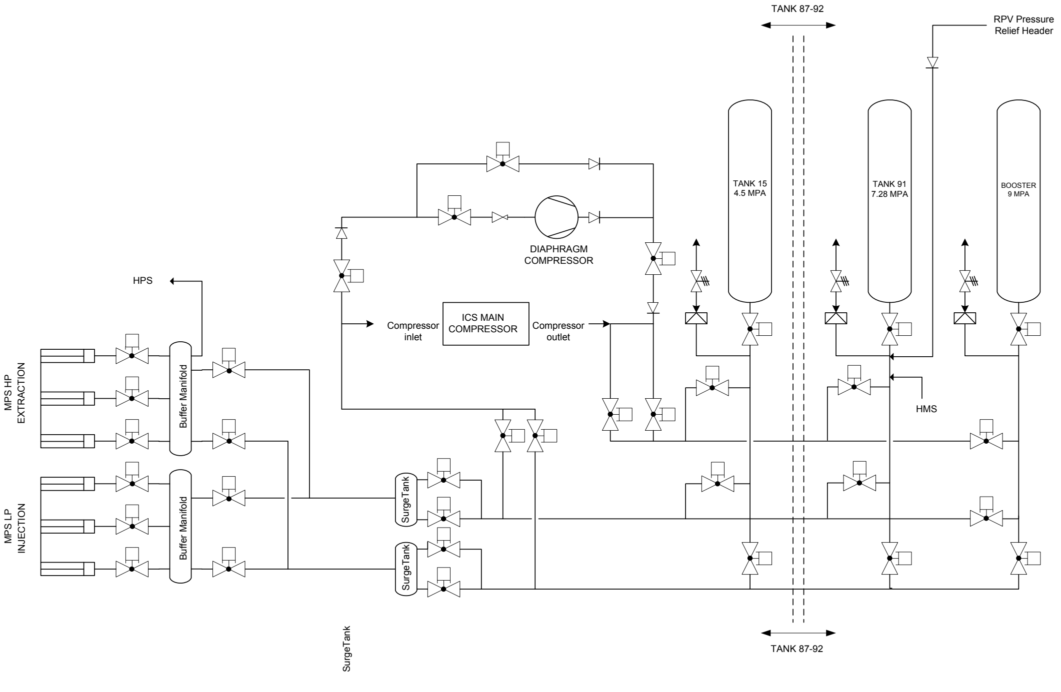

Fig. 1. ICS conceptual design of RGTT200K[10]

be replaced. The HMS injection point in the ICS is shown in the Figure 1 [12].

Helium Purification System

The Helium Purification System (HPS) has the main function to maintain the quality of helium coolant RGTT200K according the requirements established [13]. The quality requirements for helium coolant of RGTT200K are shown in Table 1.

Table 1. The gas impurities specification limit (ppmV) in the primary coolant of RGTT200K[14]

H_2O	CO_2	H_2	CO	CH_4	N_2	O_2
0.2	0.6	3.0	3.0	0.5	0.2	0.02

Gas impurities in the reactor coolant occuring during the reactor maintenance caused by the entry of H_2O and O_2 to the coolant system are known as water ingress and water ingress. The mitigating concept of impurities in the helium coolant by helium purification system is designed with the following steps:

- During maintenance activity or reactor fuel loading, the helium as primary coolant covers the material under atmospheric pressure and protects the metal / component surface. While the other component are not treated, it can be isolated to avoid water ingress by retaining helium gas at relatively high pressure [4].
- The HPS should be able to clean the gas impurities in the primary coolant so that it meets the quality requirements that have been set.

Basically, there are two kinds of impurities in the coolant i.e. solid particles (carbon dust) and gas impurities [15]. To obtain a good helium gas quality, four steps requirements should be done as shown in Figure 2 as the helium gas purification strategy.

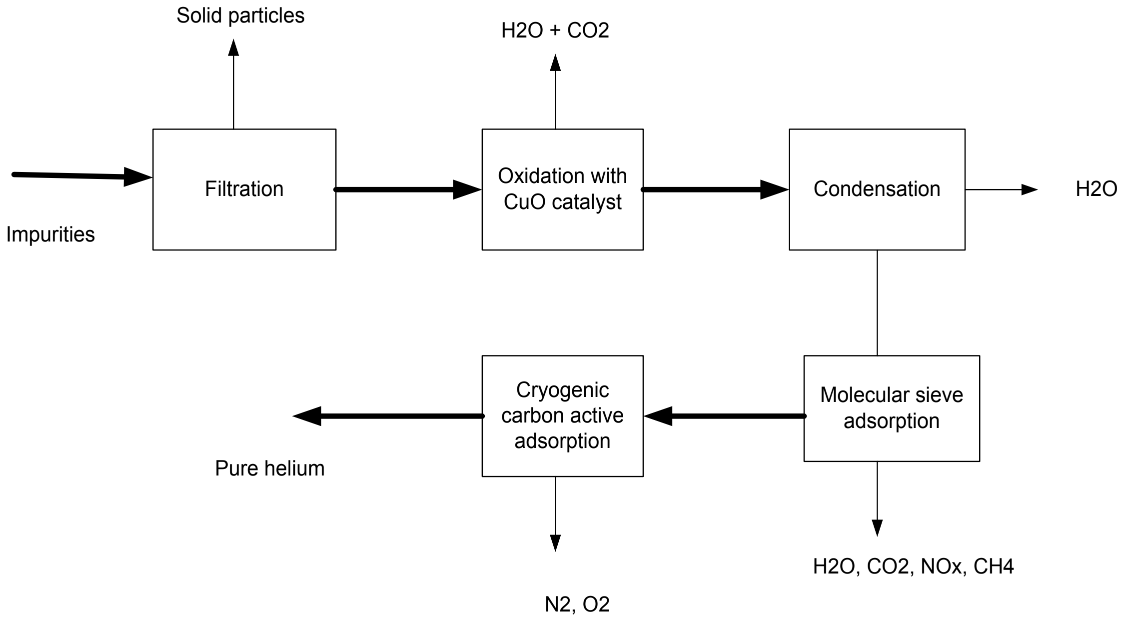

Fig. 2. Helium purification strategy in the HPS

The gas impurities come from the reaction between air and graphite resulting in H_2, H_2O, CH_4, CO, CO_2, and N_2 molecules [16]. The size of gas molecules is similar to the size of the helium gas molecules, so that a separation process strategy is necessary.

The first step is solid particles separation. Particles contained in the primary coolant are usually carbon dust in aerosol form. The cartridge filters or HEPA filters are used to separate it. Almost 99.7 % of carbon dusts are removed.

The second step is the oxidation of gas impurities. In this step a small sized gas impurities such as hydrogen (H2) and carbon monoxide (CO) are oxidized by M_xO_y metal oxide (CuO), so that hydrogen will become water and carbon monoxide according to the following reaction:

$H_2 + M_xO_y \rightarrow H_2O + M_xO_{y-1}$ ……………….……… (1)
$CO + M_xO_y \rightarrow CO_2 + M_xO_{y-1}$ ……………………… (2)
$CH4 + 4M_xO_y \rightarrow CO_2 + 2H_2O + 4M_xO_{y-4}$ ……… (3)

Thus, the existing types of gas impurities are H_2O, CH_4, CO_2, N_2, and O_2.

The third step is the condensation, as water will be condensed and separated from the other gaseous compounds. Gas that remains is a residual H_2O, CH_4, CO_2, N_2, and O_2.

The fourth step is molecular sieve adsorption. In this step the large molecules to be separated are H_2O, CH_4, and CO_2. Molecular sieve material is membranes, zeolite or aluminum oxide (Al_2O_3). The last gas impurities that remain are N_2 and O_2.

The fifth step is adsorption with activated carbon on the cryogenic condition (extremely cold condition is -180 °C). In this process, the oxygen and nitrogen have to be condensed and adsorbed, while the helium is still in a state of gas and relatively in pure condition. To obtain the high purity of helium gas as primary coolant, these steps must be accommodated or implemented in the conceptual design of the HPS. The HPS of RGTT200K conceptual design is shown in Figure 3.

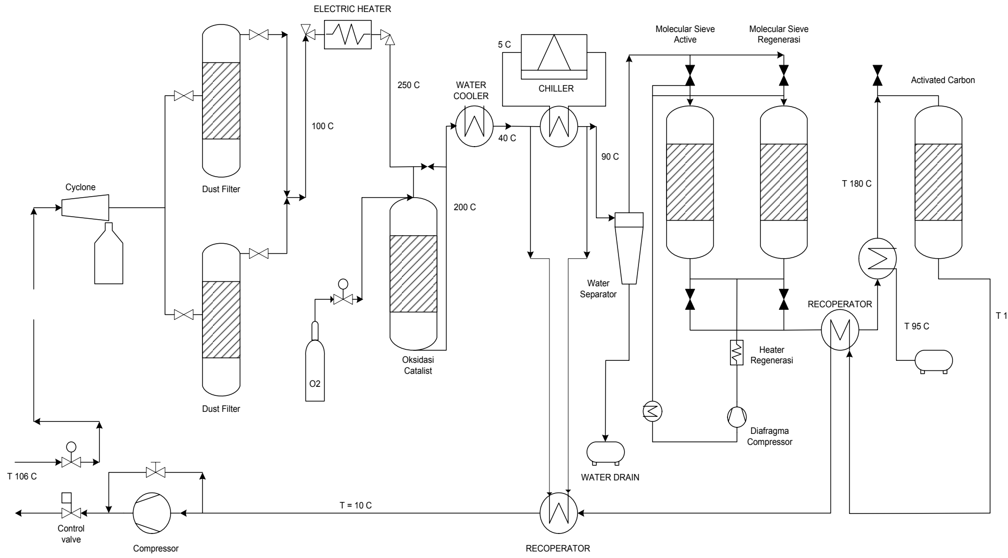

Fig. 3. Conceptual design of HPS of RGTT200K [10]

The HPS components are: heater, catalytic converters, oxygen tanks, chillier, water separator, water collection tank, recuperator, molecular sieve, liquid nitrogen for cryogenic conditions, activated carbon adsorber, nitrogen storage tanks, nitrogen pump, blower, regeneration heater, cooling water for regeneration, pressure relief valves, control valves, isolation valves, piping systems, and bursting discs.

METHODOLOGY

The power conversion unit design concept of RGTT200K consists of a turbine and a compressor on one shaft. Turbine-compressor system is placed in a pressure vessel which is coupled to an electric generator. High temperature helium gas expands through a turbine to generate rotation. From the turbine, the hot helium enters the recuperator to heat the other parts of helium from the compressor's output. Hot helium is cooled further in the pre-cooler and compressed again by the compressor into recuperator before returning back to the reactor core.

The amount of the helium pressure in the reactor cooling system must be maintained so that it does not interfere with the operation of RGTT200K. The system used to stabilize the pressure and volume of helium in the cooling RGTT200K is the HICS consisting of ICS, HPS and HMS. The ICS model is done using ChemCAD software as shown in Figure 4 [17].

The HICS of RGTT200K design refers to the same design for the PBMR South Africa [18]. In this model, the ICS is modeled with 2 pressure tanks with respectively 4.5 MPa and 7.24 MPa. The 4.5 MPa storage tank is used if the pressure in the cooling system exceeds the normal pressure (overpressure).

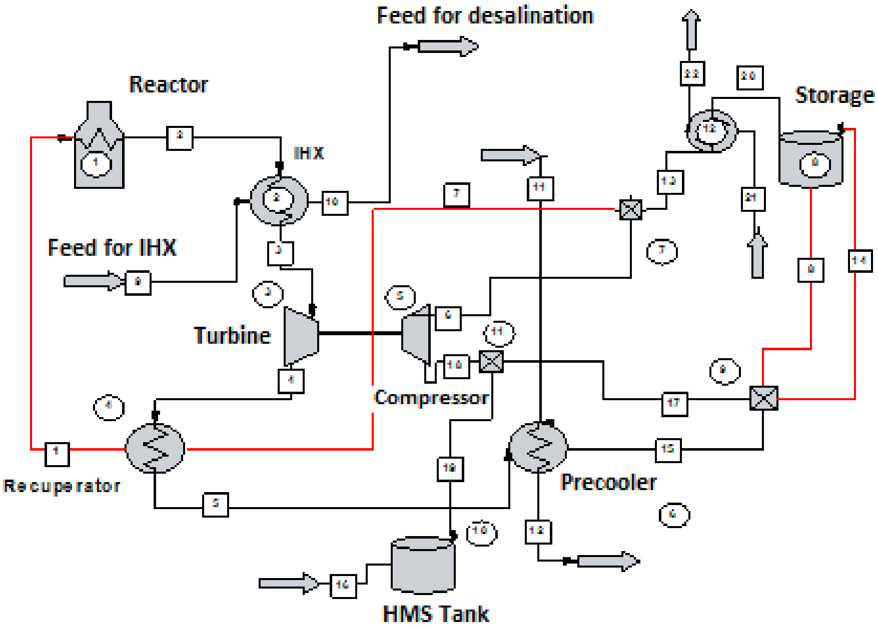

Fig. 4. The ICS model using ChemCAD

The overpressure assumed is up to 5 % of the normal operating pressure, which is 5.46 MPa (54.6 bar). If the coolant pressure exceeds the limit value of 5.5 MPa, the reactor will be shutdown automatically. The 7.24 MPa tank is used when the pressure in the cooling system is depressurized below to a maximum of 5 % under normal pressure. The specifications of primary coolant of RGTT200K are listed in Table 2.

Table 2. The specification value of RGTT200K coolant system

Reactor thermal power	: 200 MW
Reactor coolant	: Helium
Coolant Pressure	: 52 bar (5.2 MPa)
Inlet core temperature	: 630 ºC
Outlet core Temperature	: 950 ºC
Main coolant mass flow rate	: 120 kg/second
HPS inlet mass flow rate	: 1 % (1.2 kg/second)
Volume of helium storage tank	: 200 m^3

RESULTS AND DISCUSSIONS

The ICS will ensure the pressure stability in the reactor coolant system. The primary coolant pressure should be maintained at 52 bars due to the pressure magnitude caused by turbine blade movement. The pressure in the primary coolant is directly related to the reactor power output.

If the coolant pressure is higher than the normal operation, the helium gas is discharged in to the low pressure storage tank (4.5 MPa) through a high-pressure point (nozzle) near the inlet turbine. The flow will stop until the normal pressure is achieved.

If the reactor coolant is depressurized, the helium from a high pressure storage tank is injected into the reactor coolant system until the normal pressure is achieved. There are two circumstances that will occur in the cooling system, which are overpressurization and depressurization conditions. Two scenarios have been simulated in this research. First scenario is overpressurization incident and the second is depressurization incident.

The overpressurization is done by simulating the excess pressure in the coolant from 52 bars to 55 bars maximum. While the depressurization event is done by simulating up to 5 % of reducing pressure in the reactor coolant from 52 bars to 47.5 bars. The nozzle valve is assumed to be full open at 1% of mass flow rate of main primary coolant. To prevent delay pressure in the storage tanks and the coolant toward to balance value there will be a surge tank to be installed. The surge tank also avoids the small fluctuation in the mass flow rate and is to anticipate sudden changes in pressure. The injection process from a storage tank into the primary coolant can work smoothly.

The mass flow rate of the cooling system to the storage tank will be terminated when the ratio of the pressure tank to the coolant pressure is equivalent to g value. The g value is equal to one (1) or 0.97 (the maximum allowable limit value). The ICS simulation results for a 4.5 MPa tank when overpressured at 1-5 % of the value of 5.2 MPa .

normal pressure (52 bar) are shown in Table 3 and Figure 5. The duration of 160 second is needed when the primary coolant is overpressurized up to 5 %. The values of pressure in the coolant are variied ranging from 0 %, 1 %, 2 %, 3 %, 4 % and 5 % of the normal pressure. The ability of the storage tank to bleed excess pressure is up to a maximum of 5 % of the normal pressure.

Table 3. The ICS simulation results for the overpressurization up to 5 % of normal operation

Over-pressure value (bars)	Equilibrium pressure at normal operation (bars)	Duration to equilibrium pressure (second)
0 % (52)	52	0
1 % (52.52)	52	16
2 % (53.04)	52	37
3 % (53.56)	52	73
4 % (54.08)	52	124
5 % (54.6)	52	160

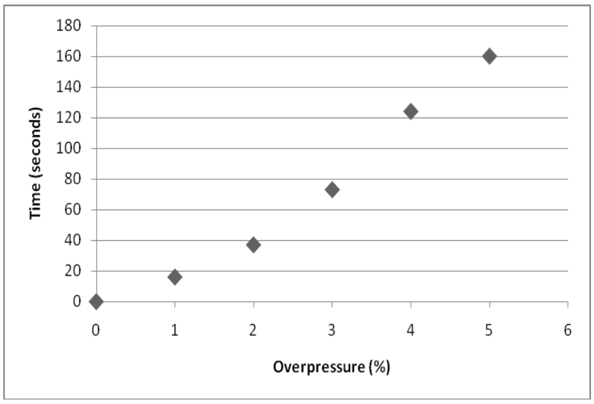

Fig. 5. Correlation between overpressure values vs duration to equilibrium normal pressure (52 bars)

The simulation results show that the duration required to return back into equilibrium normal pressure does not increase linearly with overpressure values. The larger overpressure values the longer is the duration is needed to achieve the normal operating pressure. The ICS simulation results for 7.24 MPa tank after it is depressurized up to 5 % of the normal pressure are is shown in Table 4 and Figure 6. The duration of 186 second is needed when the primary coolant is depressurized up to 5 %. The closed Brayton cycle is used to analyze the thermodynamic phenomena. This cyle consists of isentropic compression, heat addition at constant pressure, isentropic expansion, and heat release at constant pressure. The turbine and compressor are designed in one shaft, where, during the normal operation, the rapid movement of turbine blades will affect the decreasing and increasing pressure in the primary coolant.

Tabel 4. The ICS simulation results for the depressurization up to 5 % of normal

Depressuri-zed value (bars)	Equilibrium pressure at normal operation (bars)	Duration to equilibrium pressure (second)
0 % (52)	52	0
1 % (51.48)	52	25
2 % (50.96)	52	45
3 % (50.44))	52	75
4 % (49.92	52	130
5 % (49.40)	52	186

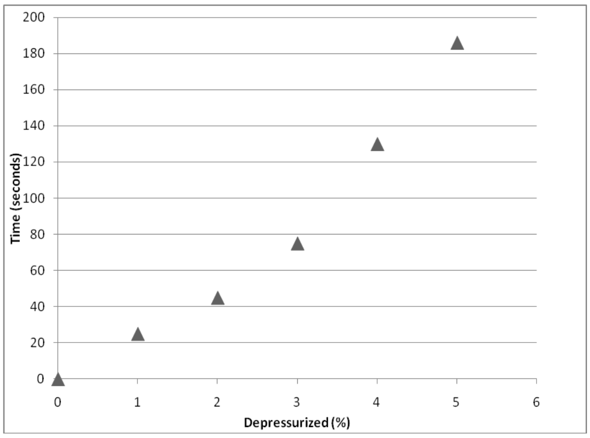

Fig. 6. Correlation between depressurized values vs duration to equilibrium normal pressure (52 bars)

When the pressure drops up to 5 % or about 5 bar then this will affect the turbine blade rotation. Due to the pressure drop, the efficiency of the turbine will decrease including the electricity generated. Under the laws of Gay Lussac, the pressure drop will be comparable with decreasing temperature. If the temperature drops, the turbine performance will also decrease, as also the efficiency of electricity generation by the generator.

CONCLUSIONS

By modelling the high pressure (7.24 MPa) and low pressure (4.5 MPa) tanks of the Helium inventory control system (ICS) using the ChemCAD software, the performance of the ICS to control the pressure fluctuation during overpressurization and depressurization in the reactor system can be simulated. The simulation results showed that the duration required for injection process from the high pressure tank to compensate the depressurization up to 5 % from normal operation was 186 seconds. And the duration for bleeding from the primary coolant storage tank due to overpressurization up to 5 % was 160 seconds. These values are still acceptable to anticipate power reactor magnitude due to pressure changes.

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