DYNAMIC SIMULATION OF LARGE SCALE HELIUM REFRIGERATOR: THE 400 W @ 1.8 K TEST FACILITY

C. Deschildre[1], A. Barraud[2], P. Bonnay[1], P. Briend[3], A. Girard[1], J.M. Poncet[1], P. Roussel[1], S.E. Sequeira[3]

[1] Service des Basses Températures, DRFMC, CEA Grenoble
Grenoble, 38054, France
[2] GIPSA-lab
Saint Martin d'Hères, 38402, France
[3] Air Liquide - DTA
Sassenage, 38360, France

Abstract

The aim of this study is to simulate the dynamic behavior of a large cryogenic refrigerator using the software Aspen Hysys®. A dynamic model of the refrigerator located at the CEA-Grenoble : the 400 W @ 1.8 K test facility, has been realized. One of the advantages of this installation is to be particularly well instrumented, thereby providing many experimental data which allows comparison between simulation and experimentation. The refrigerator comprises all the typical equipments of cryogenic systems: plate-fin counter-current heat exchangers (one of them is a liquid nitrogen pre-cooler), cold turbine expander, helium phase separators, wet pistons expander and centrifugal cold compressors. The software used is Aspen Hysys® which is provided by the company AspenTech. This is a process simulation environment first designed to serve processing industries especially Oil & Gas and Refining. Cryogenic companies already use it to simulate steady-state process in order to improve the performance of their equipment. This paper describes the model development and shows possibilities and limitations of the dynamic module of Aspen Hysys®. Thus, an experimental study has been performed to investigate the dynamic behavior of the Brayton Cycle of the 400 W test facility. Results obtained by the simulation were compared to the experimental data and have led the validation of the dynamic behavior of the model.

Keywords: Cryogenic systems, dynamic simulation, helium refrigerator.

Presenting Author's biography

ROUSSEL Pascal. Born in 1965. Diploma from ENSIEG-INPG (electrical engineer school in Grenoble) in 1988. Joined CEA-Cadarache in fusion department (TORE SUPRA) in 1990. Since 1995 works in cryogenic department: Service des Basses Temperatures at CEA–Grenoble. Involved in study design and specification of large scale cryogenic facilities (CERN-LHC, ITER, JT60SA).

1 Introduction

The aim of the study is to simulate the dynamic behavior of a helium refrigerator. The software used is Aspen Hysys® which is commercialized by the AspenTech Company. This tool is a general purpose modular-sequential process simulator used for oil and gas process, which can also cope with cryogenic process. Indeed, several cryogenic companies use it in steady state mode for design and rating purposes [1]. In petrochemical industries, the development and use of dynamic models are becoming very current [2] while the dynamic simulation applied to cryogenic systems started to spread during last five years [3]. Thus, Maekawa et al. [4] published interesting aspects of refrigeration process simulation.

The first goal of our study has been to evaluate the dynamic module of the software and then to obtain a dynamic model of our refrigerator. Located at the CEA – Grenoble, the 400 W @ 1.8 K Test Facility [5] is particularly well instrumented and comprises all the typical equipments of cryogenic system, making the system suitable for model validations.

Set up of the model has been performed step by step. First, the accuracy of the helium properties given by the software has been checked. Due to the lack of reliability below 2.2 K, the coldest part of the refrigerator has not been simulated. Secondly, cycle components were simulated alone, to finally be merged on a complete plant model.

This paper describes the model development and the results obtained.

2 The 400 W @ 1.8 K Test Facility

2.1 Process Flow Diagram

This installation which is especially dedicated to physics experiments is fully operational at nominal conditions since October 2004 [5]. It has a cooling capacity respectively of 400 W at 1.8 K or 800 W at 4.5 K and is dedicated to tests of cryogenic components or physics experiments like thermohydraulic studies on two phase superfluid helium and also for turbulent phenomena study of superfluid helium.

The refrigerator consists of a cold box connected to a warm compressor station presented in Figure 1. The cold box designed by Air Liquide comprises counter flow heat exchangers, a liquid nitrogen pre-cooler, a cold turbine expander, a wet piston expander, helium phase separators, cold valves. There are also centrifugal cold compressors and an oil ring pump.

2.2 Equipments

The warm compressor station consists in two screw compressors installed in parallel between the low pressure (LP) and the high pressure (HP) streams. They can compress a maximum mass flow of 72 g/s at the nominal pressures of these two streams (16 bars and 1.05 bars).

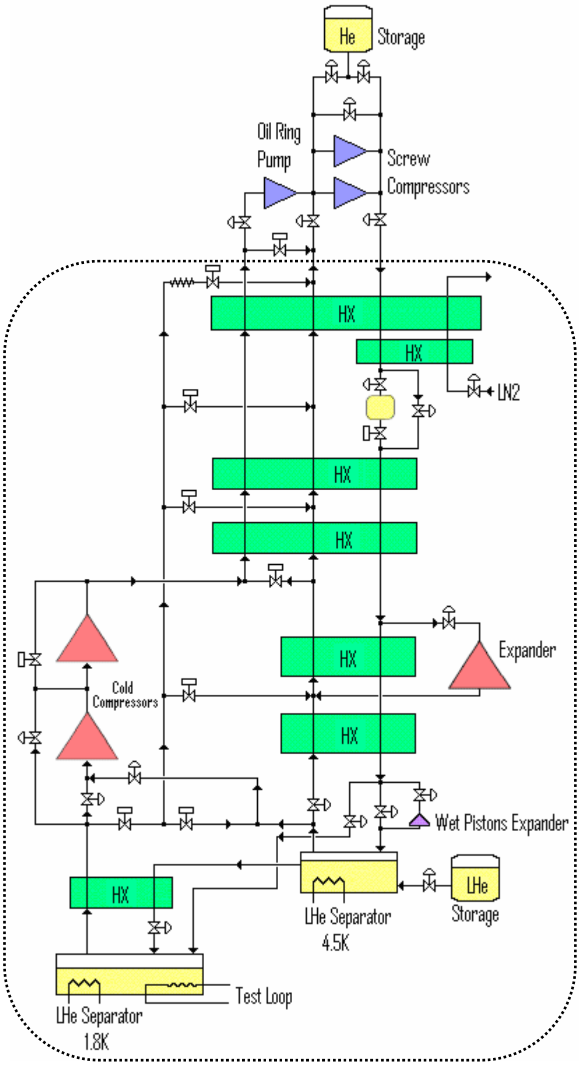

Fig. 1 Process scheme of the 400 W @ 1.8 K station

The counter flow heat exchangers are brazed aluminium plate fin heat exchanger manufactured by Nordon. They consist of fins separating sheets, forming passages which are closed by bars, with opening for the inlet and outlet of fluids.

The counter flow heat exchangers are brazed aluminium plate fin heat exchanger manufactured by Nordon. They consist of fins separating sheets, forming passages which are closed by bars, with opening for the inlet and outlet of fluids.

The first stage of the cool down is obtained by means of nitrogen thanks linked to an evaporator whose vapors are flowing through the top heat exchanger. The start up of the cold turbine expander leads to temperature lower than 80 K. Its nominal inlet temperature is about 20 K and it can treat a mass flow rate of about 30 g/s. Then, liquid helium at 4.5 K can be produced either through a Joule-Thomson (JT) valve or by a wet piston expander installed in parallel.

Liquid Helium at 4.5 K is stored in a 200 liters phase separator.

3 Development of the Dynamic Model

Aspen Hysys® uses the Euler (implicit) method and offers an equation oriented method for the calculation of the pressure and flow profile called Pressure-Flow (P-F) Solver [6]. The P-F Solver considers the integration of pressure flows balances. This method implies that one pressure (or flow) specification should be made on each boundary stream (feeds/products). So, the software will use the equipment conductance or Cv value combined with the inlet and outlet streams specifications to determine the flow rate (or pressure drop) through the equipment.

3.1 Heat Exchangers

A key point of this study is the simulation of the heat exchangers. The software makes it possible to simulate complex plate-fin heat exchanger [6]. The exchanger dimensions, the number of streams, the number of channels per stream, the arrangement of the channels, the type and the geometry of the fins, the heat transfer coefficients and the pressure drop can be specified.

The main characteristic of cryogenic heat exchanger is the temperature dependence of different parameters like heat capacity and thermal conductivity of materials. As this function is not included, additional work was carried out to express these coefficients as a function of temperature.

In addition, the heat transfer coefficients must be specified for each stream, in the software, these coefficients are constant. However, they vary with the temperature, the mass flow and the fins geometry. A function has been added to the model in order to make the heat transfer coefficients vary according to correlations such as the equation (1):

$$h = \alpha.\mathrm{Re}^{\beta}.\mathrm{Pr}^{\gamma} \qquad (1)$$

where Re and Pr are the Reynolds and the Prandtl Number; α, β and γ are coefficients depending on the fins geometry.

3.2 Cold Turbine Expander

The cold turbine expander is defined by its capacity and its efficiency. Built-in turbine expander in Aspen Hysys® considers constant values for these parameters. Therefore, a tool has been added which includes equations describing these parameters as functions of the input of the expander conditions. These equations have been established thanks to experimental data and follow equations (2) and (3):

$$Capacity = K_1 \frac{P_{in}}{\rho_{in}.\sqrt{Z_{in}.T_{in}}} \qquad (2)$$

where P_{in}, T_{in}, ρ_{in} and Z_{in} are respectively the inlet pressure, temperature, density and compressibility factor; K_1 is a coefficient determined experimentally.

$$Efficiency = K_2\left(\frac{U_1}{C_0}\right)^2 + K_3\left(\frac{U_1}{C_0}\right) + K_4 \qquad (3)$$

where $U_1 = \pi.D.N$ with D: Turbine expander wheel diameter and N: rotational speed; $C_0 = \sqrt{2.\Delta H_{S=Cste}}$ with $\Delta H_{S=Cste}$: the enthalpy difference at constant entropy; K_2, K_3 and K_4 are coefficients determined experimentally.

3.3 Helium Phase Separator

The vessel is described by its geometrical shape, its dimensions and its nozzles dimensions and positions [6]. Parameters relating to the wall: thickness, density, heat capacity and thermal conductivity can be specified, so thermal inertia is considered by the model. Finally, characteristics about the vessel heater must be defined.

3.4 Wet Pistons Expander

The wet piston expander is defined by its volumetric capacity and its efficiency. Specific performances curves can be implemented in the model if needed so that accurate behavior of an existing pump or compressor can be modelled.

3.5 Valves

In the software, three predefined types of valve can characterize the valve opening: Linear, Quick Opening and Equal Percentage [6]. An extra type of valve, called “User Table”, makes customization possible by specifying the relationship of the flow (% of max) and the opening (%). This last method has been used to simulate main valves.

Then, the flow coefficient (Cv) of the valve must be specified in order to provide valve dimension.

4 Dynamic simulation Results and Analysis

4.1 Comparison between Simulation and Experimental Results

Validation of the model thanks to comparison with experimental results is an important milestone.

Operation at nominal condition of the 400 W test facility has been realized during April 2007 and it has been reproduced by simulation to compare experimental data and simulation results.

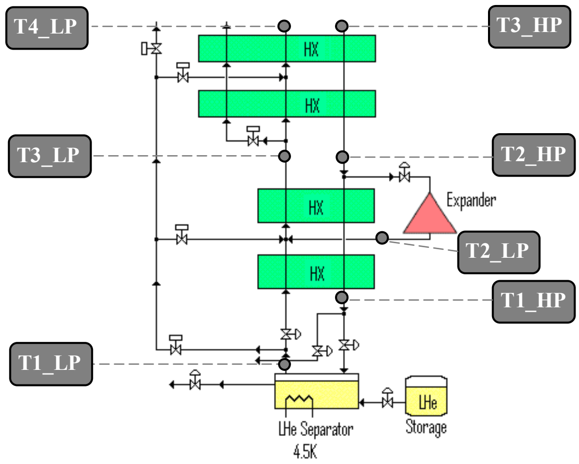

Fig. 2 Brayton Cycle

In this first study, only a part of the refrigerator, presented in the Figure 2, has been considered. The Brayton Cycle, composed of the turbine expander and associated heat exchangers, is the most reactive part of the refrigerator. The aim was to compare the dynamic behavior of the model with the experiment.

At the beginning, the system is stationary: the temperatures are stable and the power applied to the separator is remained constant to keep the liquid level at 50%. Then, the perturbation is applied to the system: the valve located upstream of the turbine expander is partially shut down from 30% to 15%.

Following this event, the cycle temperatures increase and as the separator power is maintained constant during all the study, the level of liquid decreases.

The first objective is to start with the same initial steady state as in the experimental process and then to obtain the same dynamic behavior. In order to send actual plant Data as an input to the model, model automation interfaces were access from Excel VBA. In this way, consistency between plant and model input conditions can be guaranteed.

The results obtained by simulation are presented in Figures 3, 4, 5 and 6. The initial steady state is obtained with the model and then the partial closing of the valve is simulated.

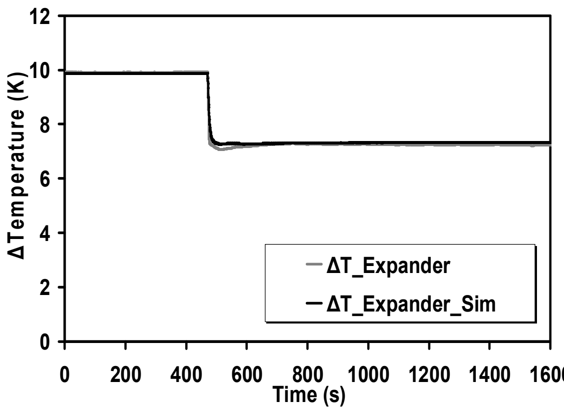

Fig. 3 ΔT across turbine expander

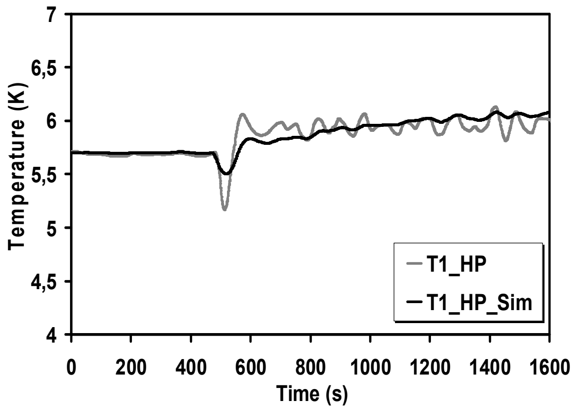

Fig. 4 Temperature upstream JT valve

The figures 3 and 4 show the temperatures evolution in the cycle. The curves in Figure 3 present the temperature difference between the inlet and the outlet temperatures of the expander. When the valve is stepped down, the flow treated by the expander and its efficiency decrease, thereby reducing the power extracted by the turbine expander and as a consequence the temperature difference across this expander. As less cold power is produced, the temperature map of this part of the cycle increases. The temperature upstream the Joule-Thomson valve is presented in Figure 4, the dynamic behavior simulated corresponds to the behavior observed on the experimental installation.

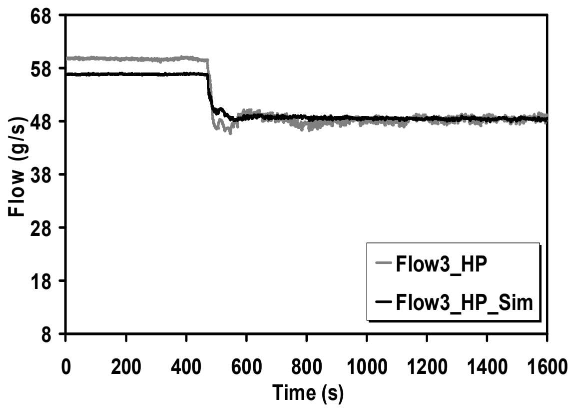

Fig. 5 HP mass flow rate

Figure 5 shows the evolution of the mass flow rate in the high pressure side. It is important to note that no specifications of flow are made, the valves are specified and mass flow rates are determined via the valve conductivity.

The power applied to the vessel is kept constant thus the liquid level decrease as shown in Figure 2d. The model reproduces the behavior and the slope observed.

The quite good agreement between experimental data and results obtained with the model has been observed, validating by the way the model.

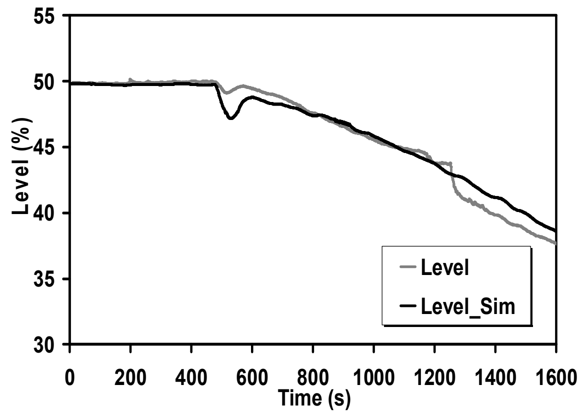

Fig. 6 Liquid level in phase separator

4.2 Dynamic Simulation using Control Tools

Feedback regulatory control can be represented using built-ins Proportional-Integral-Derivative (PID) controllers [6]. Controller behavior depends on three parameters which must be specified: K_c, T_i and T_d, in addition to the action type (direct or reverse).

Procedural control strategies are implemented into the model using the "Event Scheduler" tool. The later allows defining a sequence of tasks triggered by a pre-determined condition, as for instance: simulation time or elapsed time, a logical expression becoming true, a variable stabilizing within a given during a given time [7].

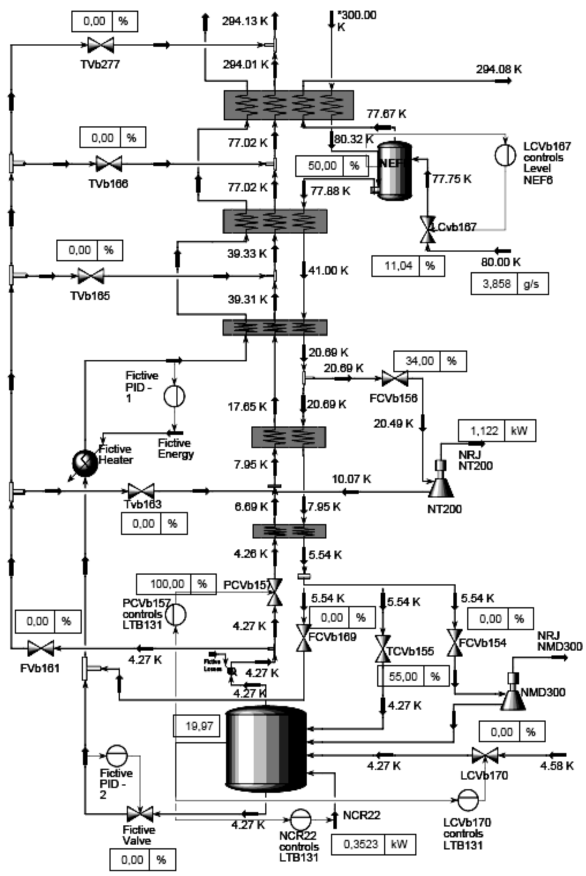

Fig. 7 Aspen Hysys® Process Flow Diagram

Therefore, dynamic simulation has been performed using the "Event Scheduler" tool and PID controllers in order to model the refrigerator behavior during the start of the wet pistons expander. Figure 7 shows the process flow diagram of the model which corresponds to the steady state preceding the start up of the wet pistons expander. The "Event Scheduler" tool has been used to reproduce the control procedure of the valve located upstream of the turbine expander (called Cv156) presented in the Figure 8 and the starting procedure of the wet pistons expander presented in the Figure 9. And a PID controller has also been implemented in the model which allows to control the liquid level via the power dissipated in the phase separator.

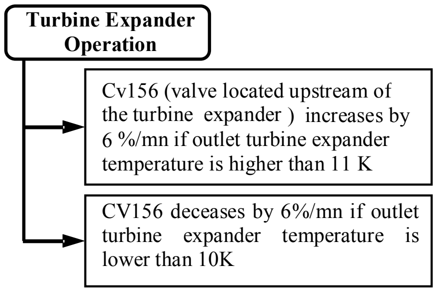

Fig. 8 Turbine Expander Operation

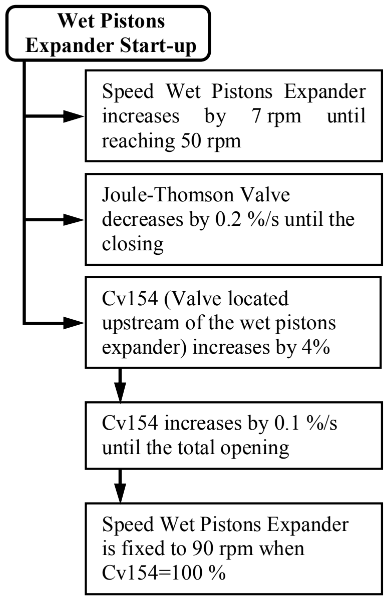

Fig. 9 Wet Pistons Expander Starting Procedure

Figure 10 shows the behavior of the valve located upstream the wet pistons expander (CV154) and the JT valve (CV155). The first opens while the other shuts in order to avoid sudden variations of global mass flow rate. The speed of the wet pistons expander sets up to 50 rpm and reaches 90 rpm when the valve is completely opened.

ISBN 978-3-901608-32-2

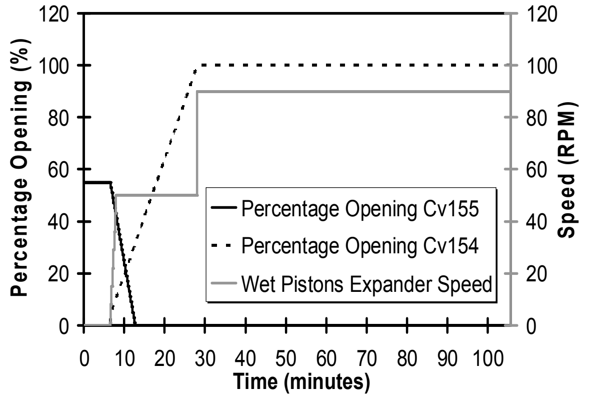

Fig. 10 Evolution of the JT valve, the valve located upstream of the wet pistons expander and its speed

Figure 11 shows the simulation results of the mass flow rate across the JT valve which varies with the opening of the valve while the mass flow the wet piston expander depends on the speed of this volumetric equipment. It also indicates that the mass flow rate cooled by the wet pistons expander is finally more important than initially in the JT valve. Thus, the refrigeration capacity of the plant is improved.

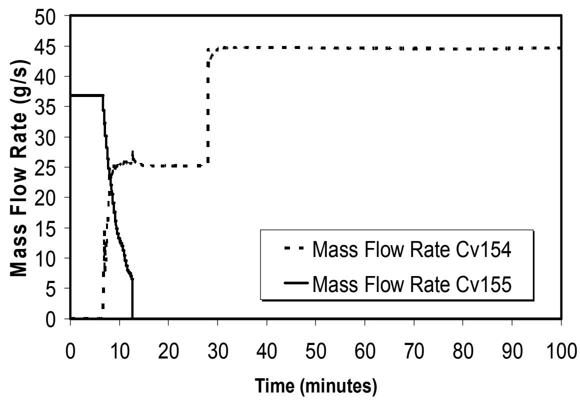

Fig. 11 Mass flow rates across the JT valve (Cv155) and across the wet pistons expander (Cv154)

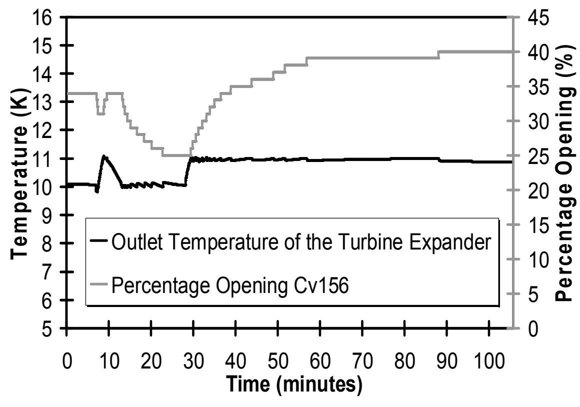

Fig. 12 Evolution of the outlet temperature and the valve opening located upstream of the turbine expander

The influence of the control procedure of the valve located upstream of the turbine expander is shown in Figure 12. The valve opens when the outlet temperature of the turbine expander is higher than 11 K and shuts down when it is lower than 10 K. Finally, the valve opening is more important when the wet pistons expander is started that when the liquefaction is produced by the JT valve, thus increasing the global refrigeration power.

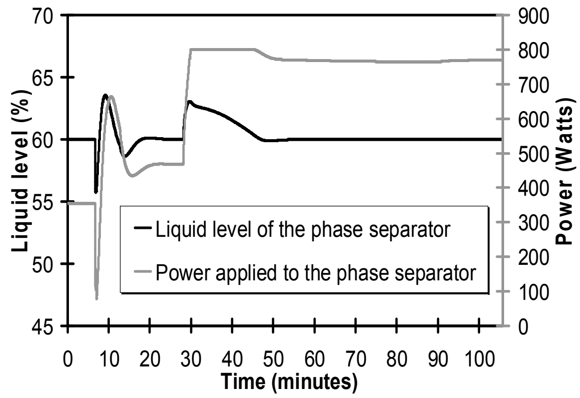

Fig. 13 Evolution of the liquid level and the power applied of the separator phase

In Figure 13, the liquid level simulated decreases suddenly. That corresponds to the real plant behavior and is due to the heat input during the start of the wet pistons expander which is at an initial temperature of 300 K. The power applied to the phase separator varies according to the PID in order to control the liquid level at 60 %. During the use of the wet pistons expander, the power available in the 4.5K helium bath is about 775 Watts instead of 350 Watts with the JT valve, according to this model. These values perfectly correspond to the capacity measurements already performed on this refrigerator. Indeed, the use of the wet pistons expander allows increasing the refrigeration power of this experimental installation .

The dynamic behavior of the model during the start of the wet pistons expander is in complete agreement with the behavior of the real plant.

By this way, the realization of this simulation has validated the implementation of control procedures and PID controllers.

5 Conclusion

Simulations have been performed in nominal conditions in order to check the dynamic behavior of the model. The comparison with experimental data has enabled the validation of this model and thereby the use of Aspen Hysys® dynamic module for the simulation of large scale helium refrigerators.

The simulation of the wet pistons expander start up has been realized using the implementation of control procedure. That shows that is possible to design and test a variety of control strategies before choosing the best suited for implementation.

Furthermore, the dynamic response to system disturbances can be examined to perform the tuning of controllers and optimize their feedback behavior [8].

Regarding the CPU time, simulation is performed more than 10 times faster than the real time with an ordinary computer: that is very satisfying.

The model developed, reproducing quite well the dynamic behavior of a real refrigerator, opens various and interesting perspectives. It can be used to train engineers and operators to the cryogenic process without adversely affecting the operation costs or safety of the plant.

Although the development of an accurate model needed considerable customization, the standard tool showed to be suitable for the work purposes. The model can be easily adapted to other installations under development to help to improve or optimize design [9].

6 References

[1] Dauguet P., Briend P., Abe I., Fauve E., Bernhardt J.M., Andrieu F. and Beauvisage J. "Kstar Helium Refrigeration System Design And Manufacturing", 24th Symposium on Fusion Technology September 2006 -, Warsaw, Poland

[2] Sequeira S. E., Graells M. and Puigjaner L., "On-line Optimization of a Paraffins Separation Plant", In FOCAPO; JF. Pekny and GE Blau, Eds. AIChE Symp. Ser., 94. (320), 15

[3] Kutzschbach A., Kauschke M., Haberstroh CCh., Quack H., "Dynamic Characteristics of a Simple Brayton Cryocycle" Advances in Cryogenic Engineering: transactions of the Cryogenic Engineering Conference – CEC.AIP Conference Proceedings, Volume 823, pp. 1987-1994 (2006)

[4] Maekawa R., Ooba K., Nobutoki M., Mito T., "Dynamic Simulation of a Helium Liquefier, ADVANCES IN CRYOGENIC ENGEINEERING: Transactions of the Cryogenic Engineering Conference - CEC. AIP Conference Proceedings, Volume 710, pp. 192-199 (2004).

[5] Roussel P., Girard A., Jager B., Rousset B., Bonnay P., Millet F. and Gully P., "The 400 W at 1.8 K test facility at CEA-Grenoble", Advances In Cryogenic Engineering: Transaction of the Cryogenic Engineering Conference – CEC. AIP Conference Proceedings, Volume 823, pp. 1420-1427 (2006)

[6] Aspen Hysys 2006 – Dynamic Modeling and Operations Guide

[7] Sequeira S.E., Romero J., Cantón, J., Graells M., Espuña A., Puigjaner L., "Supporting Batch Scheduling With External (HYSYS) Dynamic Simulation", HYPROTECH 2000, Amsterdam, 6-10 November 2000.

[8] Engell S., "Feedback control for optimal process operation", Journal of process control, Volume 17, Issue3, March 2007, Pages 203-219

[9] Contreras J., Ferrer J.M., "Dynamic simulation: a case study", Hydrocarbon engineering, 2005, vol. 10, no5, pp. 103-107

