



Transient Simulation of a Two-Stage Air Cycle Chiller

This case study demonstrates the transient operation of a two-stage Air Cycle Chiller. The chiller consists of a closed cycle in which dry air is circulated via a set of centrifugal compressors and expanded through a turbine to provide cooling at very low temperatures. A typical application is in crust freezing of pre-baked foods.

HVAC

CHALLENGE:

This case study demonstrates the transient operation of a two-stage Air Cycle Chiller. The chiller consists of a closed cycle in which dry air is circulated via a set of centrifugal compressors and expanded through a turbine to provide cooling at very low temperatures. A typical application is in crust freezing of pre-baked foods. The objective of the simulation is to model the integrated transient operation of the system together with a controller. This is required, amongst other things, to check that the compressor is never at risk of surging.

BENEFITS:

Flownex was the preferred choice of software for the following reasons:

- Transient/Dynamic simulation of the system
- Integration of a PID controller
- Ensure compressor operating points are within limits to prevent surge

SOLUTION:

The Flownex transient simulation of the two-stage air cycle chiller integrated with the PID controller showed that the temperature can be controlled effectively by varying the shaft speed of the low-pressure compressor. It also showed how the operating points of the low-pressure compressor and turbine changed in response to the operation of the system. The control implemented in the Flownex simulation ensured that the compressor operating point was always sufficiently far away from the compressor surge line during the transient.



INTRODUCTION

This case study outlines the challenge of managing the transient operation of a two-stage Air Cycle Chiller, in which dry air is compressed in two centrifugal stages and then expanded through a turbine to achieve the very low temperatures required for crust freezing pre-baked foods.

The goal was controlling the chiller's dynamic behaviour so that the low-pressure compressor never approached its surge line during startup, load changes, or shut-down sequences.

Avoiding compressor surge is critical to prevent mechanical damage, ensure uninterrupted cooling performance, and maintain consistent product quality in food-freezing applications.

By modelling the complete system in Flownex—including the chiller cycle and its PID controller—it is possible to simulate transient responses, adjust compressor shaft speeds, track the operating points of compressor and turbine, and verify that the compressor remains safe from surge throughout all phases of operation.

SYSTEM DESCRIPTION

Figure 1 below shows the Two-Stage Air Cycle Chiller system.

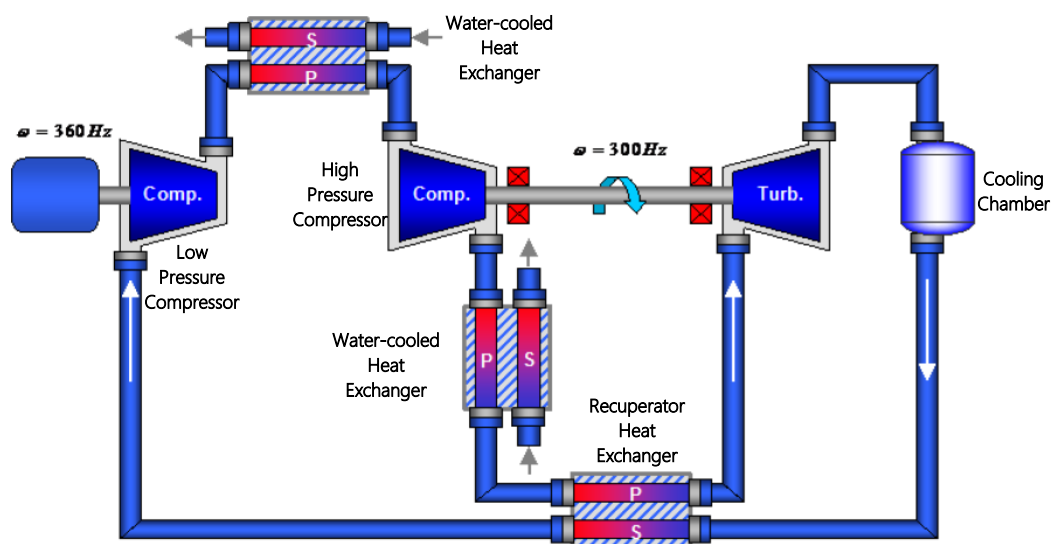


Figure 1: Two-Stage Air Cycle Chiller

The cooling chamber is operated at a temperature of -50°C and an absolute pressure of 100 kPa. Air is extracted from the chamber at a rate of approximately 1 kg/s through the secondary side of the recuperator heat exchanger, where it is heated to 30°C , after which it enters the low-pressure compressor. The compressor is driven by an electric motor via a variable speed drive. The air leaves the compressor at around 95°C and 176 kPa and enters a water-cooled heat exchanger. The air is cooled down to 40°C , after which it enters the high-pressure compressor. The high-pressure compressor is driven by the turbine via a free-running shaft. The air leaves the high pressure compressor at approximately 80°C and 245 kPa and passes through a second water-cooled heat exchanger and recuperator heat exchanger. The high pressure gas at -40°C is then expanded through the turbine to a pressure of just above 100 kPa and a temperature of -80°C , before it re-enters the cooling chamber. The operating temperature of the cycle is regulated by varying the shaft speed of the low-pressure compressor via a PID controller.

OBJECTIVE OF SIMULATION

The objective of the simulation is to model the integrated transient operation of the system together with the controller. This is required, amongst other things, to check that the compressor is never at risk of surging.

FLOWNEX MODEL

Figure 2 below shows the Flownex model.

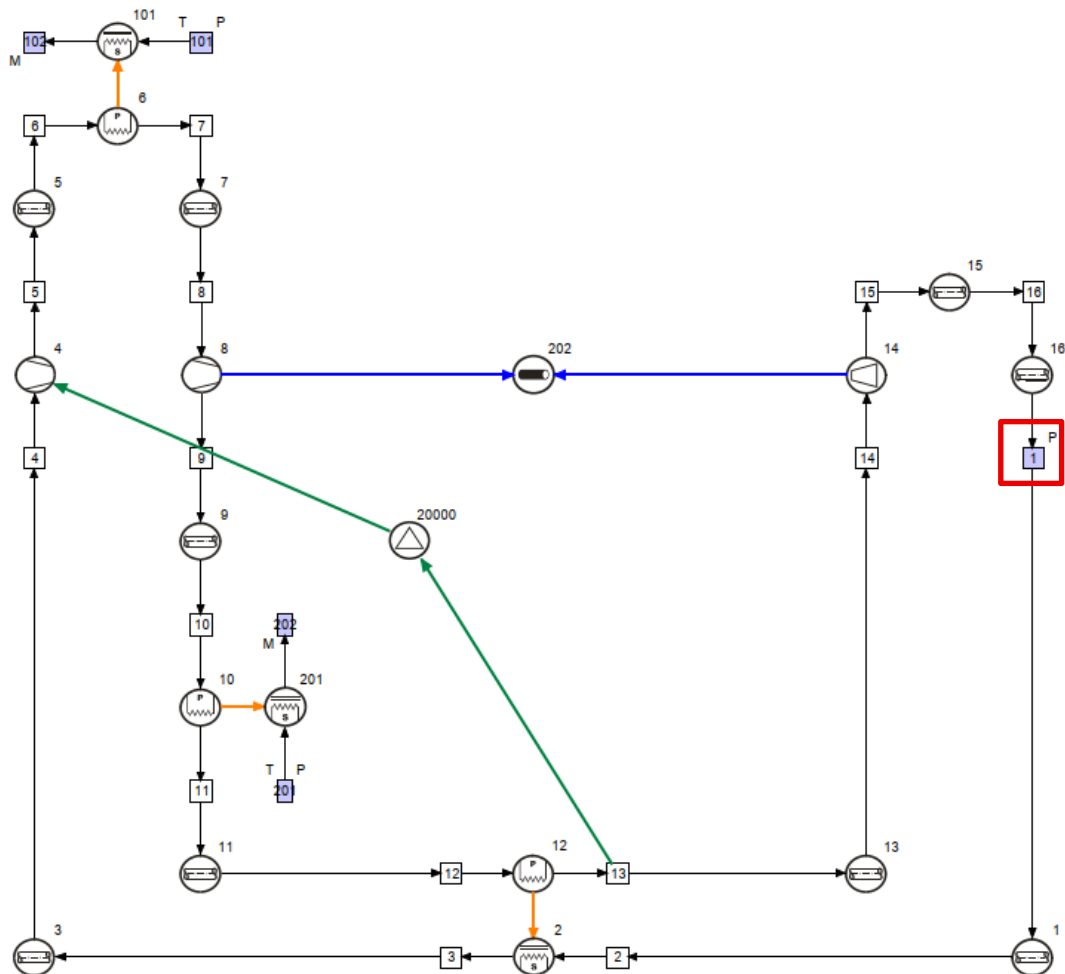


Figure 2: Flownex network of the Two-Stage Air Cycle Chiller

Node 1 (indicated by a red square) represents the outlet to the cooling chamber. Air leaves this chamber through a pipe (element 1), whereafter it passes through the secondary side of the recuperator heat exchanger. Air is compressed in the low-pressure compressor after which it is cooled though a water-cooled heat exchanger. The slightly cooled air is compressed by a high-pressure compressor, after which it is cooled though a secondary water-cooled heat exchanger. Air then passes through the primary side of a recuperator heat exchanger where it is drastically cooled, before being passed through the turbine. The loop is closed when the air re-enters the cooling chamber. The free-running shaft that connects the high-pressure compressor to the turbine is represented by element 202.

CONTROL PHILOSOPHY

The design operating heat load of 31.42 kW is specified as a heat input to pipe element 16, the inlet to the cooling chamber. The PID controller (element 20000) senses the temperature at the outlet of the primary side of the recuperator heat exchanger and regulates it to a set-point of -40°C by varying the speed of the low-pressure compressor.

DESCRIPTION OF SIMULATION

The simulation starts in steady-state with the shaft speed of the low-pressure compressor at 21 600 rpm. The temperature at the outlet of the recuperator is at -32.8°C instead of the desired -40°C .

As soon as the transient simulation starts, the controller is switched on and the controller speeds up the low-pressure compressor in order to lower the temperature at the outlet of the recuperator. After 30 seconds, an external heat load of 40 kW is introduced in the cooling chamber and after another 30 seconds it is decreased to 20 kW, with the controller and shaft speed responding accordingly each time.

RESULTS

Figure 3 below shows how the low-pressure compressor shaft speed varied over time in response to the controller regulation.

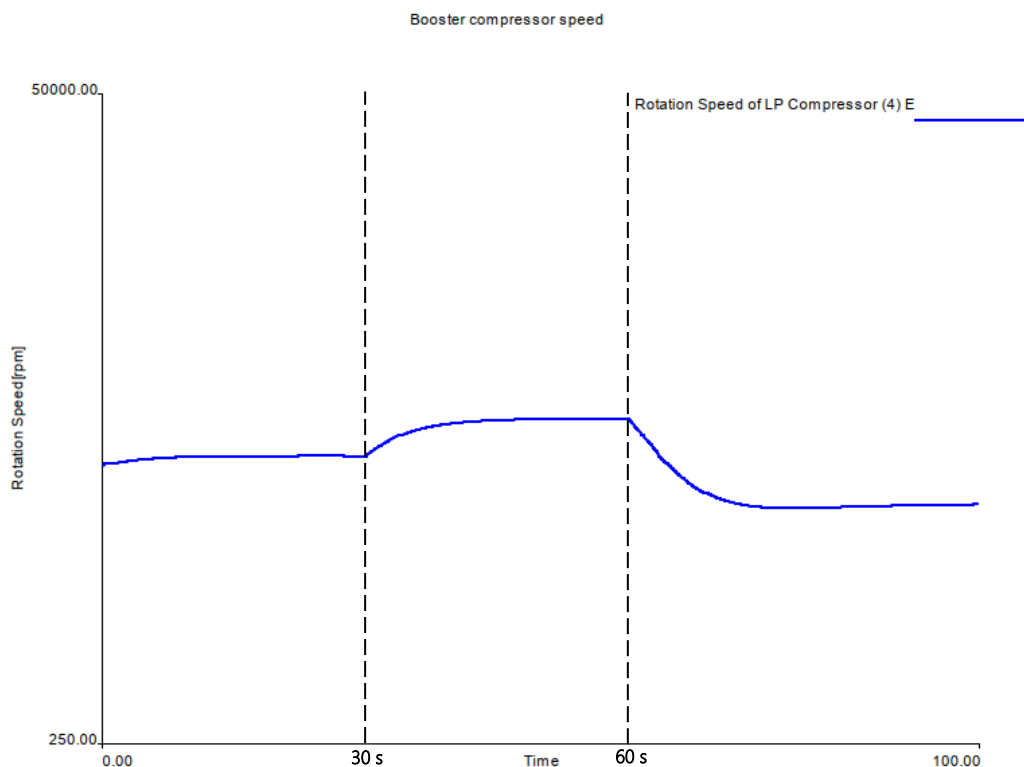


Figure 3: Low-pressure compressor shaft speed.

The shaft speed is initially increased as the controller attempts to lower the recuperator outlet temperature. At 30 seconds shaft speed is increased even more due to the greater applied heat load that increased the recuperator outlet temperature, and at 60 seconds shaft speed is reduced in response to the lower heat load.

Figure 4 below shows how the resultant temperature at the outlet of the recuperator varied over time.

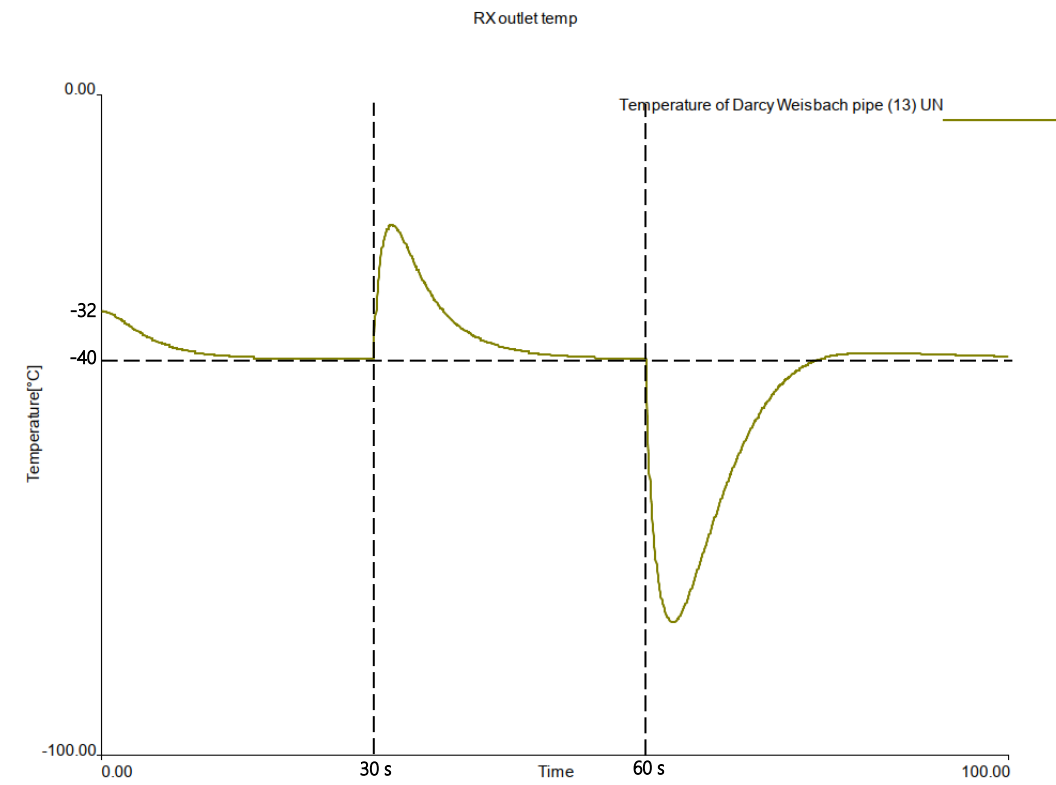


Figure 4: Temperature at the outlet of the recuperator heat exchanger primary side.

Note how the heat loads introduced at 30 s and 60 s caused the recuperator outlet temperature to fluctuate, with the controller responding to bring the temperature back to set point every time.

CONCLUSION

The transient simulation of the two-stage air cycle chiller integrated with the PID controller showed that the system supply temperature can be effectively controlled by varying the shaft speed of the low-pressure compressor. The simulation also showed how the operating points of the low-pressure compressor and turbine changed in response to the changes in the inputs to the system. The control maintained the compressor operating point sufficiently far away from the compressor surge line at all times during the transient simulation.