

RECENT PROGRESS IN DYNAMIC PROCESS SIMULATION OF CRYOGENIC REFRIGERATORS

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ABSTRACT

At the CEC 2005 a paper with the title “Helium refrigerator design for pulsed heat load in Tokamaks“ was presented. That paper highlighted the control requirements for cryogenic refrigerators to cope with the expected load variations of future nuclear fusion reactors. First dynamic computer simulations have been presented.

In the mean time, the computer program is enhanced and a new series of process simulations are available. The new program considers not only the heat flows and the temperature variations within the heat exchangers, but also the variation of mass flows and pressure drops. The heat transfer numbers now are calculated in dependence of the flow speed and the gas properties. PI-controllers calculate the necessary position of specific valves for maintaining pressures, temperatures and the rotation speed of turbines.

Still unsatisfactory is the fact, that changes in the process arrangement usually are attended by adjustments in the program code. It is the main objective of the next step of development a more flexible code which enables that any user defined process arrangements can be assembled by input data.

KEYWORDS: Cryogenic Refrigerators, Tokamaks, Computer modeling and simulation, Heat transfer

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INTRODUCTION

The periodic refrigeration requirements of the Tokamak fusion reactors had released the initial start-up to develop a computer program for the dynamic simulation of cryogenic refrigerators. It was the target of those calculations to prove the feasibility of refrigerators which can cope with periodic heat load variations and which still performs a passable efficiency.

This target principally is reached with the results which have been shown in our CEC-paper from 2005. The later improvements of the computer program all confirm those results within small margins and thus the need for further fundamental results is not compulsory. Rather a vested interest in modeling a complete refrigerator by equations and in solving them by numerical algorithms performs the driving power to continue the program development during off-time.

THE BASIS

In the time dependant approach, compared to the steady state approach, the degree of freedoms in the physical system is increased. This means more variables, more input data, and more complex solving procedures.

As additional input data there are all the parameters which contribute to the inertia of the system. This is the mass and the type of the solid material as well as the fluid volumes of each heat exchanger elements, of each piece of pipe and of each vessel in the cold box and in the compressor system.

The necessary computing power and the complexity of the solving algorithm constrain drastic simplifications compared to existing steady state application programs.

The first rough and ready program from 2005 was based on a very simple approach. Each heat exchanger element performed a constant number of transfer units (NTU) and its pressure drop for each of the included flows was constant as well. The absolute pressures in HP and LP-lines were constant and only the medium pressure line which represented the return flow from the turbines was floating according to the suction volume flow of the second compressor stage.

In the mean time, a considerable progress is achieved concerning the physical basis.

1. The heat transfer numbers are subject to the fluid properties and the Reynolds number.
2. The pressure drops per stream and element are subject to the mass flow and the fluid density
3. The absolute pressures are either floating or they are controlled by virtual valves.
4. The positions of these virtual control valves are adjusted by PI-controllers.
5. The turbine efficiency is subject to the applied pressure ratio from inlet to outlet and to the reduced rotation speed.
6. The turbine mass flow is calculated as the flow through a nozzle, roughly corrected by the influence of the reduced rotation speed.
7. The turbine rotation speed is subject to the shaft power, the current position of the brake valve. The position of this brake valve itself is PI-controlled maintaining the optimal work-rate.

All the dependencies can not hide the fact that, the approach of our computer model is still a simplification of the physical facts and solving all the physical conservation laws correctly would require a huge computer capacity. Thus the target of this development is a model which enables the simulation on a usual desk top engine, within an acceptable computing time but with transparent simplifications. What makes it so difficult to build this program?

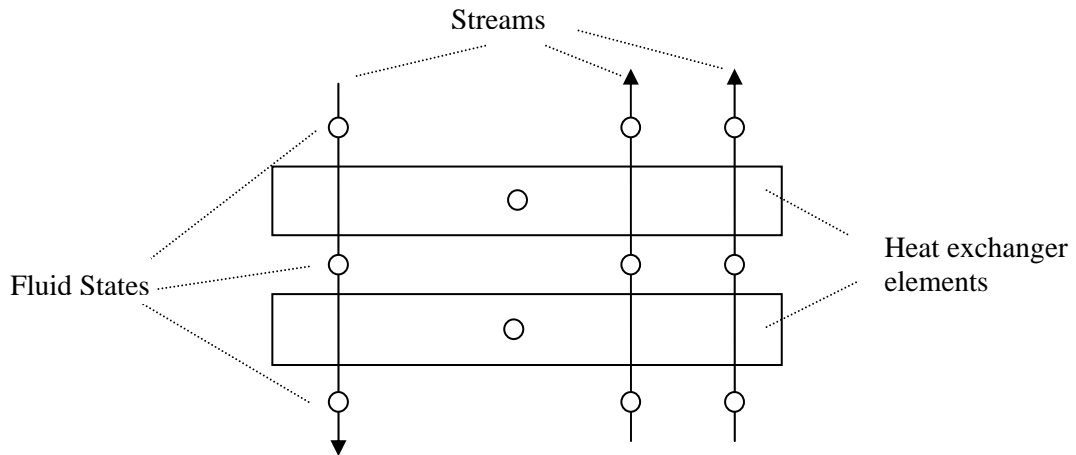


FIGURE 1. Heat exchanger elements.

THE COMPLEXITY OF DYNAMIC SIMULATIONS

The most challenging part of the program pertains the model and the solver for heat exchanger elements. In our approach, the heat exchangers are divided into elements. Each element has its individual temperature value of the solid material. It is exchanging heat with an undefined number of joining streams.

To each of the streams a volume per element is assigned. During pressure rises and during temperature drops these volumes appear as sinks of mass flow, vice versa they appear again as mass flow sources.

The thermal mass of this fluid inventory within the heat exchanger elements, which is defined by the product of mass and specific heat, is also considered. At temperatures below about 15K, this thermal mass of the fluid usually is higher than the thermal mass of the solid material and it occurs during numerical simulations that the temperature difference between solid material and fluids starts oscillating. To remove such oscillations in our approach, the total thermal mass of fluid and solid material is assigned to the solid element.

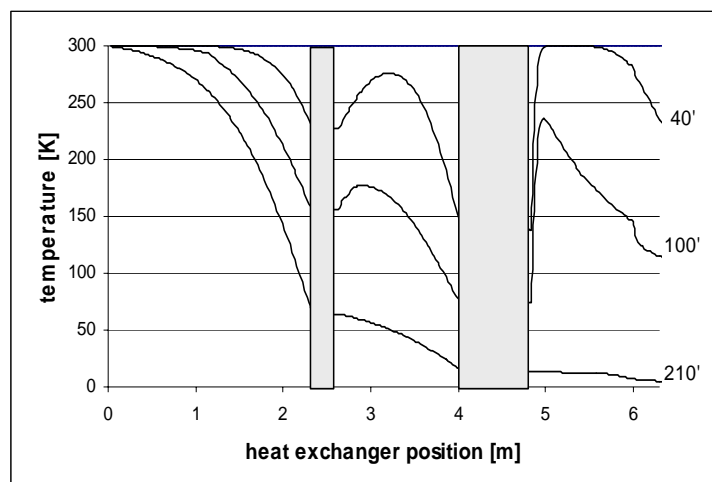


FIGURE 2. Temperature distribution along the total length of the heat exchangers during cool-down. The three curves represent snapshots at 40, 100 and 210 minutes from start-up. The grey fields indicate the ranges there the turbines are installed.

This is physically not fully correct, but it enables to apply time steps in the range of 0.1 seconds. Otherwise, to remove the oscillations, time steps in the range of 0.01 seconds would be necessary.

The heat exchanger elements make use of another simplification. The propagation of pressure variations is instant. The elements consider static pressure drops, but they do not consider pressure gradients for accelerating or slowing the flows.

The heat exchanger elements have to be short. For accurate results they must perform not more than half of a transfer unit (NTU). Since a typical small refrigerator uses 100 NTU, the simulation process has to consider at least 200 elements. The reason for this limited heat transfer is, that the elements do not distinguish between parallel flows and reversed flow. The typical effect of a counter flow heat exchanger arises by way of connecting multiple elements.

With all the simplification, still per stream and per element there is one equation for the heat balance, one equation for the pressure drops and one equation for the conservation of mass to be solved. These equations are using fluid properties like density, temperature, enthalpy, internal energy, thermal conductivity and viscosity. The relations between all these values are performed by the state equations for helium from NIST [1] and this makes it necessary that each single time step has to be solved iteratively.

SOME RESULTS

The last phase of the cool down of a refrigerator or liquefier is one of the most difficult transients to be simulated. Before the partial condensation of the Joule Thompson flow begins, the temperatures and the densities in the lowest heat exchanger are strongly fluttering, and with the start of the condensation they stabilize again. This is explained by the specific heat of the heat exchanger material (aluminum) which is only about one thousandth of the specific heat at ambient temperature. The FIGURES 3 and 4 show calculated results from this phase.

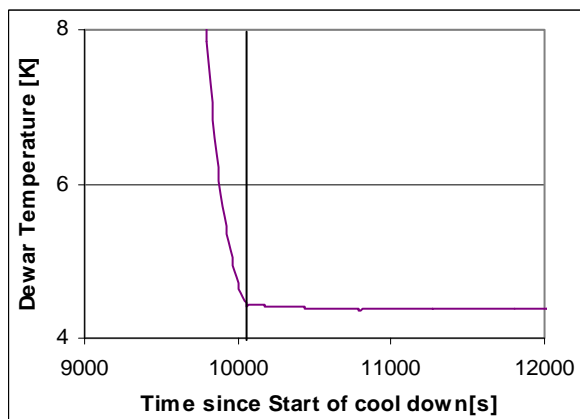


FIGURE 3. The dewar temperature at the end of the cool down operation. The vertical line marks the beginning of condensation. The indicated time is measured from the beginning of the cool-down at ambient temperature.

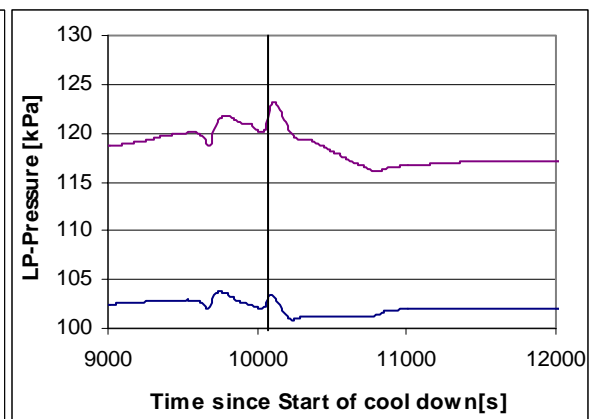


FIGURE 4. The pressure fluctuations in the low pressure line at the end of the cool down operation when partial condensation of JT-flow begins. The upper curve represents the pressure in the separator, the lower one the pressure at warm end.

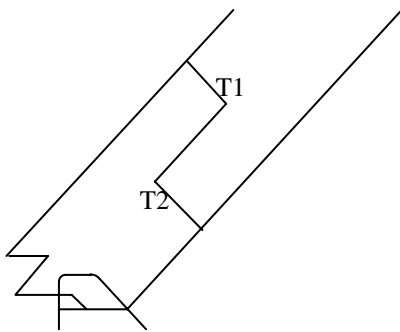


FIGURE 5. Process arrangement (Entropy-Temperature-Diagram) with two pressure levels and two serially connected turbines (T1..T2). Typical arrangement for small standard refrigerators and liquefiers.

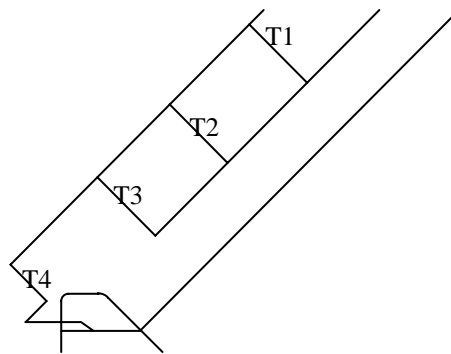


FIGURE 6. Process arrangement (Entropy-Temperature-Diagram) with three pressure levels and multiple turbines (T1..T4) in parallel at different temperature levels. Typical arrangement for large applications.

THE PROGRAM DEVELOPMENT

The currently existing program code is far away from being a shareable computer application with operating instructions for everybody. The prototypes have been developed with the objectives of a transparent physical approach and a maintainable demand of computing time. More practical, the aspects of the applicability have been discounted. A weak spot in the applied solving method is that changes in the process arrangement usually are attended by adjustments in the program code.

The FIGURES 5 and 6 show two different process variants which need to be simulated with different programs. The two programs are using the same modules for heat exchanger elements for turbines, for compressor simulation and for control valves, but for the interplay between these modules, different iteration loops must be applied.

The process variant of FIGURE 5 which is used for smaller units like the Linde L-series refrigerators and liquefiers requires a more complicated solver than the process variant of FIGURE 6. The reason to this is, that the parasitic coupling between the two turbines in FIGURE 5 is more intensive than it is between the turbines in FIGURE 6.

On the way to a sophisticated dynamic program which enables to compose all types of refrigerators by simple input elements, a new trial has been started a few months ago. The direction of impact is a fully linearized system with independent variables, such as fluid temperature, fluid density, solid temperature and mass flow. Transformed in this way, a typical small refrigerator yields to a diagonal linear system of approximately 2300 equations with a band width of 22 unknowns in each equation.

The current state of this new program is that it starts operating. The cool down operation of a standard process from ambient temperature down to a steady state operation as liquefier or refrigerator runs successfully. Rather difficult, with the linearized system, is the startup of a simulation as well as the sudden changes of heat loads or valve positions.

CONCLUSIONS

On the way to a shareable computer application for the dynamic simulation of cryogenic refrigerators and liquefiers different prototypes have been developed. Starting from a very simple approach, in the first phase the physical completeness and correctness has been improved and tested.

The target of the current second phase is a code which enables to compose different process arrangements by input data. This code has produced already first encouraging results.

Still unsatisfactory is the comfort in using the program. The time and the effort for modeling a refrigerator and for preparing all the input data like weight and flow cross-sections of heat exchangers and piping is enormous. The buildup of a comfortable user interface is not yet started.

It is not the purpose of this program to replace existing computer programs for the steady state process calculations of cryo-plants. For the process design and also for the off-design calculations of download operations steady state calculations are more effective.

The value of the new program is that difficult transient operating modes can be traced in the design phase of a refrigerator. The simulation further is helpful for testing control programs in absence of the real refrigerator and it enables to find optimal control parameters. Worth mentioning that such a program is applicable for the education of engineers and operators.

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