Dynamic Simulation of Brazed Plate-Fin Heat Exchangers

D. Averous[1], K. Hammadi[2], H. Pingaud[2] , X. Joulia[2] , P. Guittard[3]

[1]NORDON CRYOGENIE SNC, 25 bis, rue du fort, B.P. 87, 88194 Golbey Cedex, France

[2]Institut National Polytechnique de Toulouse (I.N.P.T.)
Ecole Nationale Supérieure d'Ingénieurs de Génie Chimique (E.N.S.I.G.C.)
Laboratoire de Génie Chimique (L.G.C., U.M.R. C.N.R.S. 5503)
18 chemin de la loge, F-31078 Toulouse Cedex, France
Tel. : (+33) 5 62 25 23 56 ; Fax. : (+33) 5 62 25 23 18 ; E-mail : Herve.Pingaud@ensigct.fr

[3]PROSIM SA, 132, route d'Espagne, 31100 Toulouse, France

ABSTRACT

In this paper a dynamic simulator of Brazed Plate-Fin Heat Exchangers (PFHE) ProSec^{TM} is presented. A rigorous model is used which allows one to represent the very broad range of configurations for this kind of equipment. A DAE solver (DISCo) is used with a sparse direct solver (MA38) to handle the large number of equations. Applications for control and design are highlighted through an industrial case study involving shutdown.

Keywords : Dynamic Simulation , Modelling, Plate-Fin Heat Exchanger, Differential-Algebraic Equations

INTRODUCTION

Plate-fin heat exchangers (PFHE) have been used frequently in cryogenic process industries for more than forty years. Thousands of units have been manufactured and are now in operation all over the world. Applications for air and gas separation are the most commonly known, but many other processes use this type of equipment now, such as recovery of natural gas, helium refrigeration, separation of H_2 and CO, ammonia production, oil and gas processing, nuclear engineering and syngas production. Almost all processes require advanced control systems in order to operate safely (to avoid equipment failure) and economically (to maintain optimal operating conditions).

A primary feature of cryogenic processes is the need of thermal integration. Saving energy can be performed very efficiently by PFHE which promote exchange between many streams simultaneously (cases with more than 12 streams are not uncommon). All streams, involved in the heat exchange, flow through a single piece of equipment. Therefore, the thermal integration translates into a physical and functional integration of process streams in the exchanger unit, frequently called the « cold box ». Even though PFHE are selected for optimal design of modern processes, this choice leads to some difficulties for the process engineer : since any perturbation on a stream entering the PFHE is propagated to the other streams, other hot and cold duties will also be disturbed. The PFHE spread the perturbations to all of its immediate surroundings. Thus, with this choice of technology, understanding the dynamics becomes difficult due to the complex coupling of streams. So, the transient behaviour of the process is intimately linked to the performance of the PFHE. That is why dynamic simulation of PFHE is recognised today as a key factor for progress in the control area of cryogenic processes.

Though, maintaining optimal steady state operating conditions is the goal, PFHE are also subject to some operating constraints in order to avoid major breakdown of the process. A dynamic simulator will provide an estimation of the constraints with respect to time and allows one to check the consistency of the control policy, especially in the start up and shutdown conditions. This is a second kind of application for the simulator : the design of safe procedures.

MODELLING AND NUMERICAL ASPECTS

Basically, a brazed plate-fin heat exchanger consists of stacked corrugated sheets (fins) separated from each other by flat plates and sealed along the edge with bars (Alpema, 1994). As we can see in figure 1, they are outfitted with inlet and outlet ports for streams. Each stream is distributed between different layers to create the stacking layer pattern. Fins lead to an important extended surface.

In the past, a number of mathematical models have been proposed for steady-state simulation, such as Haseler (1983), Pingaud (1988) and Prasad (1997). Pingaud (1989) covered dynamic simulation but used assumptions of Kao (1961) to limit the size of the problem.

In order to obtain a model formulation with general applicability, the exchanger is split into a sequence of two types of elementary zones : distribution zones, where the main purpose is to facilitate the inlet and/or outlet of streams, and exchange zones where fins are chosen specifically to improve the heat exchange.

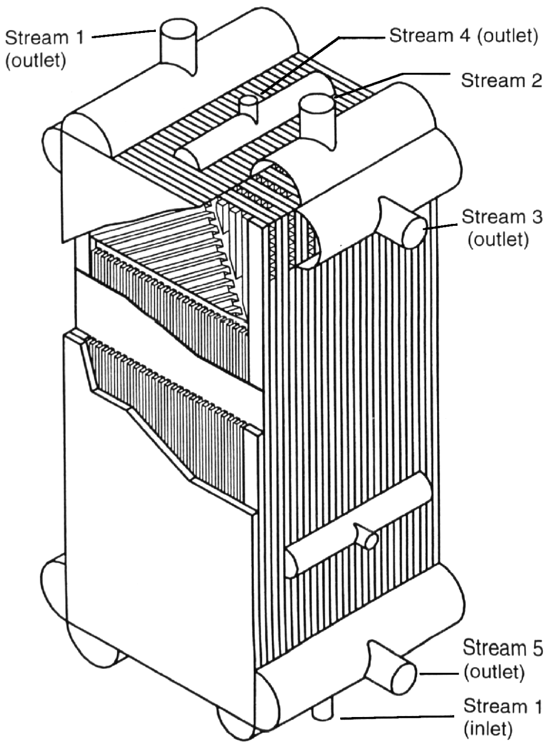

Figure 1 Brazed Plate-Fin Heat Exchanger

The sequence of zones follows the device structure and the topology of the streams (figure 2). In order to be able to represent the internal changes of PFHE, we have used a rigorous model with the following classical assumptions :

1. temperature in a passage is considered uniform over a cross-section ;
2. there is no fluid maldistribution across the width ;
3. temperature change across a parting sheet is negligible ;
4. heat accumulation in fluids is negligible.

To analyse the internal behaviour of the device we have taken into account the following points :

1. all stacking pattern are treated with transversal and longitudinal conduction ;
2. insulation losses by cap sheets and side bars are integrated ;
3. heat transfer coefficients and pressure drops calculations are evaluated with an in-house correlation linked with the manufacturer's data base.

Generally speaking, process modelling is based on conservation laws for mass, momentum and energy. Because of the assumptions, only heat balances have to be considered here. Heat is transferred between adjacent passages directly through the separating plates and by conduction through the fins. Due to the transversal and longitudinal conduction, temperatures are strongly linked. Because streams can enter every where in the exchanger, it leads to a Multi-point Boundary Condition problem. Hereafter are the general descriptive equations, for a given layer and plate i (except for the first i=1 and last plate) :

$$D_i \frac{\partial H_i}{\partial z} = hA_i^{eff}(T_i^p + T_{i+1}^p - 2T_i) \qquad \textbf{(1)}\text{ fluid}$$

$$\begin{aligned} -\rho C V_i \partial z \frac{\partial T_i^p}{\partial t} = {} & h_{i-1} A_{i-1}^{eff} \partial z \left(T_i^p - T_{i-1}\right) + \\ & h_{i-1} \eta'_{i-1} A_{i-1}^{s} \partial z \left(T_i^p - T_{i-1}^p\right) + \\ & h_i A_i^{eff} \partial z \left(T_i^p - T_i\right) + \qquad \textbf{(2)}\text{ plate} \\ & h_i \eta'_i A_i^{s} \partial z \left(T_i^p - T_{i+1}^p\right) + \\ \lambda_i^z \ell e_i \frac{\partial Tp}{\partial z}\Big|_z & - \lambda_i^{z+\partial z} \ell e_i \frac{\partial Tp}{\partial z}\Big|_{z+\partial z} \end{aligned}$$

For equation 1, the right hand side corresponds to the convection with both upper and lower plates. For equation 2, the two first terms of the right hand side correspond, respectively, to the convection and conduction with the lower layer and plate; the two next ones with the upper layer and plate; the last term is the longitudinal conduction.

Starting from data which contain the topology of the process streams in a PFHE and the geometrical data, set of equations for the whole exchanger is created. It leads to a system of Partial Differential Algebraic Equations (PDAE). After a proper discretization, this is then reduced to a system of Differential Algebraic Equations (DAE). This system includes physical discontinuities, such as phase changes of a stream and technological discontinuities, mainly changes of fin types. In order to tackle these problems, a new generation of DAE solver, named DISCo, has been developed (DISCo 1998). This DAE solver, originally based on a modified version of the LSODI implementation (Hindmarsch, 1980) for the Gear's method, has been improved and designed in order to solve such problems efficiently. The sparsity of the jacobian matrix is exploited in order to cope with large systems of equation. For this the MA38 linear solver (Duff and Davis,1997a) is used.

As an illustration of abilities of ProSec, an abrupt complete shutdown of a process stream and its influence on both the process and internal aspects is analysed.

CASE STUDY

The case is derived from an industrial case. Below we give a brief description :

Number of streams	5	Width	0.760 m
Number of passages	79	Length	6 m
Number of equations	25324		

Table 1 Case study specifications

Schematically, the stream pattern can be depicted on the box without a true representation of the header positions. As shown in figure 2, there is a redistribution of stream C : the layers freed by D are used by C. In this zone only E is present and the others layers are dummy passages.

Stream A enters the exchanger in liquid state and must exit in vapour state due to the presence of a compressor. The state events "temperature of stream A equal to dew point" is automatically detected by DISCo.

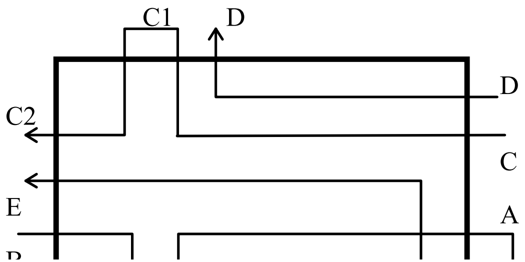

Figure 2 Topology of streams

The exchanger is divided in a 150 cell grid (variable cell size) along the length, leading to a system size of 25324 equations.

We will study the dynamic response of the heat exchanger when stream E is shut down in 5s, after 10s of steady-state operation. This can be seen as a failure scenario. The results from both the manufacturer's point of view (technological constraints) and the process engineer point of view (i.e., the influence on others streams) will be analysed.

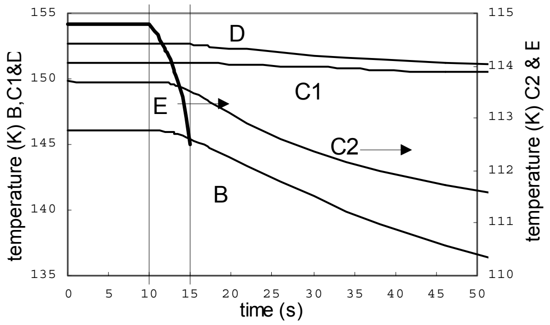

Figure 3 Outlet temperatures during perturbation

The figure 3 represents the first 50s of the perturbation. The response to the shutdown, though, is not immediate. The metal mass of PFHE works as a buffer.

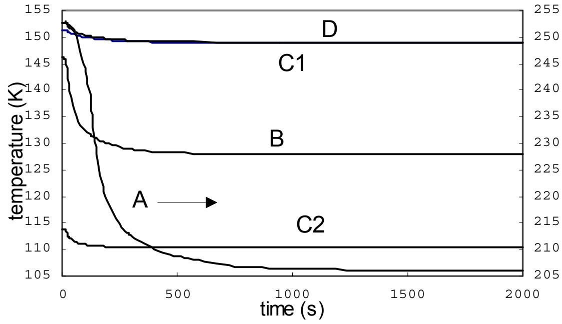

Figure 4 Exit temperatures versus time

The figure 4 shows the complete response. The new steady-state occurs after about 1250s for stream A and even more quickly for others. The perturbation propagates to others streams, especially those which are liquid-vapour (B and A). This can dangerously affect the process.

In figure 5 the exit composition of A is shown. Due to the influence of stacking arrangement, its layers exhibit a difference in their output quality and dynamics. The bold curve (A output) corresponds to overall mass vapour fraction (adiabatic mixing of all output stream A layers). The two other curves (slowest and fastest) correspond to the two extreme layers with respect to the response delay to the perturbation. The stream starts leaving the exchanger below its dew point at t=121.7s.

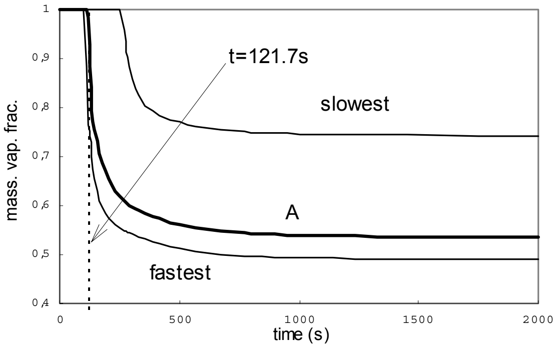

Figure 5 Exit mass vapour fraction of stream A

In figure 6, we see the phase change front inside the exchanger from the initial vapour to the final liquid-vapour state along the length of the fastest layer. The influence of this moving front is visible on the maximum stacking plate temperature difference as well as on the maximum between two adjacent plates.

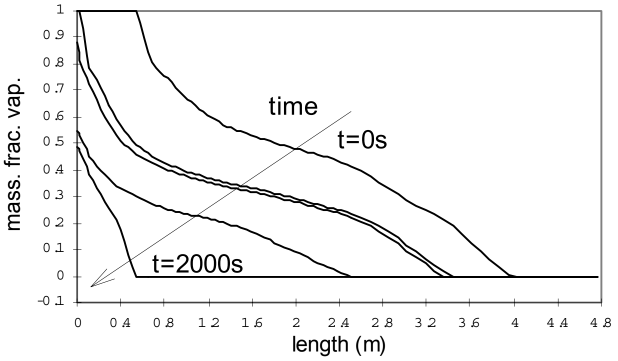

Figure 6 Evolution of state change front

In figure 7 we show the evolution of the position and value of maximum plate temperature difference. From a value of about 28.4° at 1.32m it ends to 40.6° at 0.13m at final steady-state.

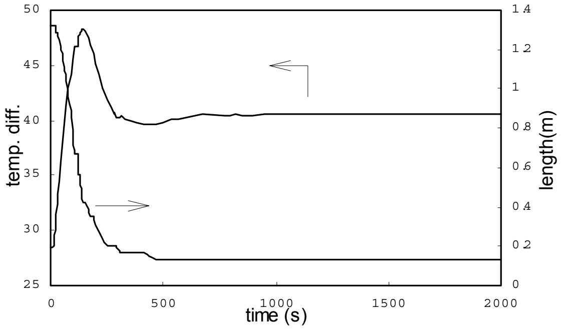

Figure 7 Position and value of maximum plate temperature difference over time

However, it is interesting to see that, due to the difference in fluid response dynamics , the temperature difference reachs a maximum before stabilisation. This behaviour is not uncommon and dynamic simulation is the only way to track this kind of path.

Position and value of maximum temperature difference between two adjacent plates over time is shown in figure 8. The maximum is reached quickly in the distribution zone at the PFHE hot end. Due to the presence of the headers, though, this zone may be more sensitive to mechanical stress created by the temperature difference.

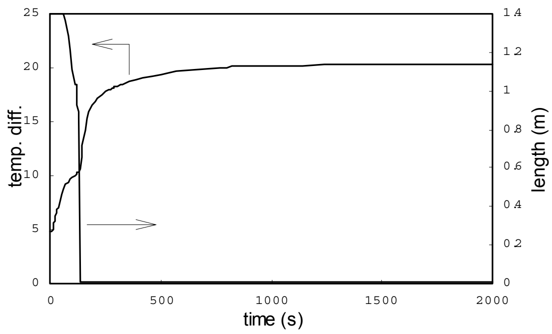

Figure 8 Position and value of maximum temperature difference between two adjacent plates

CONCLUSION

In this paper, a new dynamic simulator of PFHE, ProSec^{TM}, has been briefly presented. The DAE solver DISCo is very efficient, giving results on large size problems that exhibit special features (discontinuities of functions due to phase transition, external disturbances...)

The use of the simulator leads us to a better understanding of the device and its dynamic. For the manufacturer, it has helped in proposing better and safer designs as well as policy for start-up, shutdown or case change. In a near future, additions should be made to the simulator to address flowsheet level analysis and the dynamic behaviour of commonly encountered processes.

Acknowledgements

This work has been performed with the financial and technical support of Nordon Cryogénie Snc. and the Association Nationale de la Recherche Technique (ANRT).

We would like to thank Dr. J.M. Le Lann and A. Sargousse for their work on DAE solver DISCo.

NOMENCLATURE

a : half fin height [m]

A^{eff} : efficient surface area between a plate and a passage by unit of length , $A^{eff} = A^{p} + \eta A^{s}$ [m^2.m^{-1}]

A^{p} : primary surface area between a passage and a plate by unit of length [m^2.m^{-1}]

A^{s} : half secondary surface of fins by unit of length [m^2.m^{-1}]

C : metal specific heat [J.kg^{-1}.K^{-1}]

D : mass flow rate [kg.s^{-1}]

e : plate thickness [m]

h : heat transfer coefficient of stream [W.m^{-2}.K^{-1}]

H : specific enthalpy [J.kg^{-1}]

ℓ : exchanger core width [m]

m : parameter defined by, $m = \sqrt{2h/(\lambda\delta)}$

N : fins frequency [m^{-1}]

perf : rate of fins perforation

T : fluid temperature [K]

T^{p} : plate temperature [K]

V : volume of metal per passage per unit length [m^3.m^{-1}]

z : length [m]

Greek letters :

δ : fin thickness [m^{-1}]

η : fin efficiency defined by, $\eta = \tanh(ma)/(ma)$

η' : by-pass efficiency, $\eta' = \dfrac{\coth(ma) - \tanh(ma)}{2ma}$

λ : conductivity coefficient of metal [W.m^{-1}.K^{-1}]

ρ : density [kg.m^{-3}]

Subscript :

i : layer or plate index

REFERENCES

Alpema, 1994, The standard of the brazed Aluminium Plate-Fin Heat exchanger Manufacturers, Association, Alpema, Houston, Texas

Davis T.A., Duff I.S. , 1997a, An unsymmetric-pattern multifrontal method for sparse LU factorization, TR-94-038, and in the *SIAM J. Matrix Analysis and Applications*, January.

Davis T.A., Duff I.S., 1997b, A combined unifrontal / multifrontal method for unsymmetric sparse matrices, TR-97-016,and in the *ACM Transactions on Mathematical Software*, (accepted, under revision).

Le Lann J.M., Sargousse A., 1998, DISCo : résolution des systèmes algébro-différentiels - Panoply of DAE integrators dedicated to solve complex chemical engineering problems, Internal Report, User Manual

Haseler L.E., 1983, Performance calculation method for multi-stream plate-fin heat exchangers. *In Heat Exchangers, Theory and Practice*, eds J. Taborek, G.F. Hewitt and N. Afgan. Hemisphere Publishing.

Hindmarsch A.C., 1980, LSODE and LSODI : two new initial value ordinary differential equation solvers, *ACN SIGNUM Newsletter* 15(4),19-21

Kao S., 1961, A Systematic Design Approach for a Multistream Exchanger With Inter-connected Wall, *ASME Paper 61-WA-255*

Pingaud H., 1988, Simulation statique et simulation dynamique des échangeurs à plaques brasées, Phd Thesis, Institut National Polytechnique de Toulouse.

Pingaud H., Le Lann J.M., Koehret B., 1989, Steady-state and dynamic simulation of plate fin heat exchanger, *Comp. chem. Engng*, Vol. 13, No. 4/5, pp 577-585.

Prasad B.S.V, 1997, The Thermal design and rating of multistream plate-fin heat exchangers*, Proc. of the Int. Conf. On Compact Heat Exchangers for the Process Industies*, june 22-27,pp 79-100.

ProSec™ : Logiciel de Simulation des Echangeurs de chaleur Compacts, User Guide, ProSim SA