INTENSIFIED AND HIGH PERFORMANCES THERMOSYPHON REBOILERS APPLICATION TO THE OIL AND GAS PROCESS INDUSTRIES

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Intensified and high performances thermosyphon reboilers: Application to the oil and gas processing industries

Abstract

The main purpose of this project was to improve and develop high efficient evaporators and reboilers, used in the oil and gas processing industries, by introducing innovative technologies. Process intensification has been achieved by reducing the size of the equipment and increasing heat transfer, which lead to higher heat recovery and lower energy consumption. In order to reach these objectives, both innovative technologies and accurate design methods have been developed. Finally, promotion and diffusion of the results towards end-users have been emphasised by evaluation of the technical and economic feasibility.

This project has focused on both tube and plate fin bundles applied to the oil and gas processing industries, and dealt with:

- the establishment of thermal and hydraulic performances of innovative surfaces under actual flow conditions (boiling of hydrocarbons) ;
- the development and the validation of a new design methodology, based on local and overall flow modelling ;
- the construction and the test of a 5 MW pilot unit incorporating enhanced tubes ;
- the test of a vertical intensified plate fin thermosyphon;
- the organisation of a seminar (Grenoble, France, 29-30 June 2000);
- the promotion and the diffusion of innovative enhancement techniques for reboilers.

The programme has successfully reached its objectives with the contribution of 4 EU countries. The work has been conducted by R&D laboratories (Greth, IKE and NTUA), with a strong industrial participation: including tube and heat exchanger manufacturers (Ciat, Nordon and Wieland), engineering and software companies (Technip and CS) as well as end-users (Shell and Targor).

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OBJECTIVES

This report presents the results of a European project dedicated to the improvement and the development of high efficient reboilers used in the oil and gas processing industries. Process intensification is achieved by reducing the size of the equipment and increasing heat transfer, which lead to a higher heat recovery and lower energy consumption.

This project has clear industrial objectives:

- the establishment of thermal and hydraulic performances of innovative heat transfer surfaces under actual flow conditions (boiling of hydrocarbons);
- the development of a new design methodology, based on local and overall flow modelling;
- the construction and the test of a 5 MW pilot unit incorporating enhanced tubes.

The objectives have been reached with the active participation of 10 partners including 7 industrial companies (CIAT, CS-Informatique, Nordon, Shell, Technip, Targor and Wieland) from 4 countries.

In a first step, several innovative boiling structures have been developed and tested using hydrocarbons as working fluid. Upon the four geometries tested, the tube No.4 has the higher thermal performance especially for low and intermediate heat fluxes (10 to 30 kW/m²). With propane, heat transfer coefficients between 12 to 20 kW/m²K were measured for a saturation temperature of 293 K. This corresponds to a factor 3 increase compared to plain tubes and a factor 2 increase compared to low fin tubes. The best enhanced boiling tube has been selected, and then tests on a bundle of 45 tubes with the same operating conditions have been performed. The data obtained have confirmed the performances measured on single tube experiments and it has been decided to build a 5 MW pilot unit incorporating theses new enhanced tubes. The selected case is a C3 splitter reboiler in a polypropylene plant.

In parallel with this experimental work, a design method has been developed and implemented in software. This new design method allows simulating and predicting the thermal and hydraulic performances of reboilers including recirculation effects.

The main industrial benefits concern manufacturers of heat equipment and end-users:

- innovative heat exchanger design and geometry, which allow an increase of 50% to 300% in heat transfer performances;
- high heat transfer performances which allow a significant size reduction, up to 50%;
- capability to achieve higher heat recovery and lower energy consumption up to 50%;
- reduced capital cost, even taking into account higher unit cost of the enhanced tube, 15% to 30% cost reduction may be expected;
- higher safety, by reduction of the liquid inventory;
- more energy efficient process schemes.

TECHNICAL CONTENT

Industrial background

Shell side boiling in horizontal tube bundles is used in a variety of heat transfer applications in the chemical and petrochemical industries, and the heat transfer and fluid flow processes are significantly different from what occurs in in-tube flows. To numerically model and to simulate the overall performances of such heat exchangers, information on two-phase heat transfer, pressure drop, etc. are required. Application to bundle boiling of correlations or models obtained for boiling on single tubes or in-tube flows is inappropriate and leads to inaccurately designed units. The design methods used for sizing reboilers are based on simplified models, which do not take into account the actual two-phase flow pattern in the bundle. For single tube boiling of pure fluids, data and design methods are available in the open literature, but for an entire tube bundle with process fluids basic information and reliable predictive methods are still not available. Enhanced structured surface tubes (re-entrant cavities that promote nucleate boiling) have been studied for refrigeration application, with fluids such as CFC or HFC. But these fluids do not allow any extension to process fluids, as the structured tubes are sensible to thermo-physical properties such as surface tension, viscosity or molar mass. These properties are significantly different for refrigerants and hydrocarbons (propane, propylene, etc.)

Process industries are very conservative regarding innovative technologies and use well-established and proven technologies (plain tubes). The first reason is that the process industry deals with a variety of fluids and in the case of mixtures the physical properties are not always accurately known. As there is a lack of data and reliable design methods, especially with non-plain tubes, design engineers will select conventional solutions. Secondly, the capital costs of heat transfer equipment are rarely a significant fraction of the product costs, and any shut down of the plant will cost considerably more than the cost of the individual unit. This latter reason must be balanced when the energy consumption represents a significant amount of the running costs. In this case, the use of enhanced tube bundles is cost effective and an energy efficient alternative technology to plain tube units. Heat transfer enhancing techniques involved in the present project will apply to the oil and gas processing industries which currently use conventional plain or finned tube heat exchangers (about 90 % of the total market).

Development of a high performance boiling tube

Experiments have been conducted at IKE (Stuttgart University) with one smooth reference tube and four variations of enhanced tubes with structured surfaces. The tested structured tubes with re-entrant cavities (outer diameter 19.05 mm) are new developments of Wieland Werke AG, Ulm. The main heat transfer area of these heat exchanger surfaces is located in the tube wall and consists of sub-surface channels and cavities. These internal structures are connected to the surrounding fluid by small openings, e.g. slits and pores. The dimensions of the sub-surface geometries are all in the sub-millimetre range.

All tubes were made of carbon steel St35.8 and as working fluid the hydrocarbon propane was used. The experiments were carried out with single tubes and mini bundles (two tubes inline) at saturation conditions corresponding to temperatures between 253 K and 293 K. The employed heat fluxes ranged from about 2 kW/m^2 to 100 kW/m^2 for single tube experiments and from about 2 kW/m^2 to 70 kW/m^2 for mini bundle experiments. The obtained heat transfer coefficients of the enhanced surfaces were compared with the results of the smooth reference tube to calculate the respective improvement factors (table 1).

Heat flux (kW/m^2)	2		10		50		100	
Saturation Temperature	253 K	293 K	253 K	293 K	253 K	293 K	253 K	293 K
Smooth	0.6	2	1.6	4.2	4.2	7.9	6.8	10.6
Variant 1	0.6	4.5	2.7	9.5	7.4	15.2	10.1	18
Variant 2	0.8	3.6	3.1	7.9	7.3	10.8	8.5	11
Variant 3	1.5	3.5	4.4	8.5	10	13	12	14.9
Variant 4	1.5	5	3.6	13.5	11.3	20	14.6	18.3

Table 1 Ranges of heat transfer coefficient α (kW/m^{2}K) of the tested tubes for saturation temperatures of 253 K and 293 K

The enhanced tube variant 4 shows the best heat transfer coefficients for all tested saturation temperatures. This variant was chosen to be used for the bundle tests at GRETh and to be employed in the shell-and-tube heat exchanger prototype.

Experiments with mini bundles, i.e. two tubes inline, were carried out at IKE to investigate the influence of the two-phase flow from the lower tube on the heat transfer of the upper tube. The tests were carried out with a mini bundle consisting of smooth reference surfaces and two mini bundles each employed with one type of enhanced tube, variant 1 and variant 4.
In the mini bundle tests with smooth tubes the upper tubes have always higher heat transfer coefficients than the lower tubes. For low heat fluxes the upper tubes show higher heat transfer coefficients by a factor of about 1.4 and for high heat fluxes by a factor of about 1.2.
In the mini bundle experiments with enhanced tubes variant 4, the results indicate that for low heat fluxes the upper tube shows higher heat transfer coefficients than the lower tube. With increasing heat flux the differences between the lower and the upper tube become smaller and for high heat fluxes almost no differences can be found. The results for low heat fluxes indicate a strong influence of the two-phase flow from the lower tube on the heat transfer of the upper tube. This influence decreases with increasing heat flux.

Bundle experiments

Tests on a small bundle of 45 tubes have been performed at Greth. The test rig consists of a bundle of tubes, which is fed by sub-cooled hydrocarbon (pentane or propane). The fluid is partially vaporised in the bundle. To evaluate the thermal performances, an overall heat transfer coefficient is given for the entire bundle. The local analysis has shown that there is no significant bundle effect and that the heat transfer coefficient seems almost constant along the bundle. Furthermore for a constant heat flux, increasing the mass flux does not affect the heat transfer coefficient. This indicates that the heat transfer mechanism is nucleate boiling and that the convective effects are negligible.

There is a relatively good agreement (up to 25% difference) between the data obtained at IKE on the two-tubes experiments and the data obtained at Greth. Several reasons can explain these results:

- the rising two-phase flow affects the heat transfer performances in the bundle experiments,
- the heating modes are different : constant heat flux at IKE and water heating at GRETh,
- impurities in the fluids.

Based on the data generated at IKE and Greth is has been decided to manufacture a pilot unit incorporating the new enhanced tubes.

Compact thermosyphon reboiler

Two prototypes of compact thermosyphon reboilers have been developed by Nordon and tested by Greth during this project. The first prototype has been tested with natural and forced convection and acts as a reference. The second prototype is much more compact and omits the shell that is conventionally used.
The results have shown that the new design has similar thermal and hydraulic performances but is significantly more compact than conventional thermosyphon reboilers. This implies energy savings for manufacturing the unit and allows (for a given space) a more efficient heat exchanger. Furthermore, as the unit is more compact and as the shell as been suppressed, the liquid inventory can be reduced to 20% of the initial value, this allows dynamic control of the system.

Modelling

Local approach
In the frame of the present project NTUA has undertaken the task to develop computational models based on the commercial CFD code PHOENICS to simulate the two-phase flow and heat transfer in bundles both in pool boiling and flow boiling (in crossflow mode). A model for the simulation of the NORDON type compact two-phase thermosyphon reboiler has also been developed and implemented in the above commercial code.
A small-scale tube bundle (a two-tube bundle) has been modelled so that the local phenomena (influence, which the adjacent tubes, exert on each other) can be investigated. Close interaction with IKE that was carrying out the heat transfer and visualisation experiments in the two/three -tube bundle was essential. Parts of large-scale tube bundles (the ones tested at GRETh) have also been modelled. These were bundles with 9 rows and two or three tubes per row. Close cooperation with GRETh that was carrying out the experimental work has proved valuable. Comparison with the computational results of GRETh, using a simpler technique (porous medium) to represent the bundle was also of great importance. In both cases, automatically generated body-fitted-coordinate computational grids were used, so that the tube diameter, pitch and spacing could be easily varied for parametric studies.
The results were physically plausible and they were compared with the measurements and observations at both IKE and GRETh showing good qualitative and quantitative agreement.

Overall 2D approach

Horizontal tube heat exchangers are widely used in chemical industry as condensers as well as evaporators. Traditional design methods for these heat exchangers are very empirical, and it is partially due to the fact that local experimental and numerical investigations on this kind of reboilers are particularly difficult to perform. Due to the complexity of the problem, they have begun very recently to produce results. During this project, GREThˈ has performed a numerical investigation using the computer code MC3D (Multi-Components 3 Dimensions).

The results of these investigations have demonstrated the applicability of the model and its performance to describe more precisely the phenomena that occur in kettle reboilers in comparison with one-dimensional models.

The advantages of this kind of model are:

1. Horizontal variation of different parameters can be shown: liquid/vapour velocities, heat transfer coefficient, heat flux, saturation temperature...
2. It locates precisely the recirculation centre and shows the recirculation phenomenon.
3. Vapour and liquid velocity can be plotted separately.
4. It allows performing parametric studies to verify the influence of geometrical modifications like shell or bundle diameter.

In the computer code MC3D, it is possible to adjust different constitutive laws for friction on tubes and momentum exchange between the two phases. These friction laws inside the bundle have been adjusted during this project on one-dimensional « Ivanoe » experimental program. But studies on liquid-vapour momentum exchange outside the tube bundle still have to be done to adjust the code more correctly. Other improvements have to be made in a future work: to consider the friction with the wall of the shell for the recirculating liquid, to operate with other fluids and to incorporate correlations for improved tubes.

Overall 1D approach

Design methods for kettle reboilers are based on a simplified geometry and require empirical correlation for predicting the recirculation flow. To overcome these problems it has been decided to develop an easy-to-use software for the design of industrial reboilers (work performed by Cisi). The design method is implemented for only one vertical plane of the boiler, with given conditions for the in-tube flow. The flow and heat transfer around tubes of the bundle is calculated with a refined mesh. Only one half of the boiler is calculated because of the symmetry of the bundle.

A new design method for reboilers, with simulation of flow and heat transfer in the bundle, has been implemented in the solver of the handbook software. The efficiency of model and numerical method of the solver has been tested by comparisons with experimental data from the literature and calculations with a two-phase flow three-dimensional software. Compared with existing tools, this solver better calculates the recirculating flow in the bundle and so, the heat transfer coefficient distribution.

Development of a pilot unit

In preparation of the field test with the enhanced tubes in the C3 splitter reboiler in a polypropylene plant at Targor in Knapsack, a thermal design has been carried out by Technip. The revamp of the existing heat exchanger with an increased and improved solution has been realised in April 2000. Concerning the supply of the enhanced tubes for the field test, Wieland has carried out screening tests using prototypes; these first tests have been quite successful. Thereby it is confirmed that the tube structure can be fabricated with the given tools and that the tube dimensions required for the field test can be achieved (10 m long U-bent tubes). The heat exchanger has been manufactured by Ciat according to the Targor specifications.

The general characteristics of the prototype are:

- TEMA type BXU horizontal
- shell diameter : 1.022 m
- number of tubes : 1150
- tube length : 5.25 m
- tube diameter : 19.05 mm
- total heat transfer surface : 360 m²

The thermal performances of the new heat exchanger have been measured and are higher than the design values. Overall heat transfer performances up to 3800 W/m² K were measured (90% improvement compared to plain tubes). To achieve these high values double enhanced tubes were adopted allowing increasing both the inside single-phase heat transfer coefficient and the outside boiling heat transfer coefficient. The initial heat exchanger had an overall heat transfer coefficient of 2000 W/m²K and the temperature approach was more that 3 K.
The level of performances reached allows increasing the production capacity by more than 20% keeping the hot source identical. The temperature approach is below 1 K, which gives a thermal effectiveness of more than 90%. Significant energy saving is also achieved as no extra heating source is required.

RESULTS AND CONCLUSION

Within the frame of this project, a new high performance boiling tube has been developed. Through a complete set of testing ranging from single tube experiments, bundle experiments (1 m²) and full size unit (360 m²), the thermal performances have been checked.
The major applications envisioned are for propane splitters and LNG applications. For short and medium term developments, propane splitters seem to be the most appropriate application, and within the frame of this project field tests have been carried out in a polypropylene plant. The first application of the new high performance boiling tube in a base-load LNG-plant will be a development that will take some time as only few new base-load plants are built world-wide.
For the LNG application, the chilling train has been evaluated using conventional design and the technology developed is this project. Within some assumptions, the total length of the heat exchanger is reduced from 67 m to 37 m leading to a weight reduction from 433 tons to 269 tons. Furthermore the liquid inventory of the chillers is reduced from 241 to 172 tons of hydrocarbons, reducing the impact in case of troubleshooting and providing a better controllability. The economic impact has to be evaluated taking into account the optimisation of the process, the cost of the equipment, but also the civil infrastructure and piping.

Deliverables

Item	Type	Partner
A enhanced boiling tube for the process industry	D	Wieland
A database for boiling on enhance tubes	K	IKE
A software for 2D simulation of reboiler	S	CEA-Greth
A software for overall simulation of reboiler	S	CEA-Greth and CS
A novel concept of compact reboiler	D-K	Nordon
A prototype reboiler	P	Targor
A report on enhanced technologies	R-K	CEA-Greth

D: device, K: knowledge, P: prototype, R: Report, S: software

EXPLOITATION PLANS AND ANTICIPATED BENEFITS

- CEA-Greth will introduce the major non-confidential results of this project in his technical handbook, which is provided to more than 120 industrial European companies.
- The software, developed by Cisi, will be included as a new tool in the Greth technical handbook.
- The exploitation of the results by Wieland is concentrating on applications of the GEWA-PB tube within ethylene plants (Technip) as well as C3 chiller reboilers in the propane precooling system of baseload LNG plants (Shell). In parallel, all other applications with shellside boiling of C3 within chemical or petrochemical plants will be considered within the ongoing technical marketing activities.
- After the tests performed at GRETh on a small unit (70 kW), if the results are promising, Nordon will try to elaborate a demonstration project based on the work performed in this project.
- At NTUA, the heat exchanger models developed will be included in PHOENICS. Application Album in one of the future releases of PHOENICS.

ILLUSTRATIONS

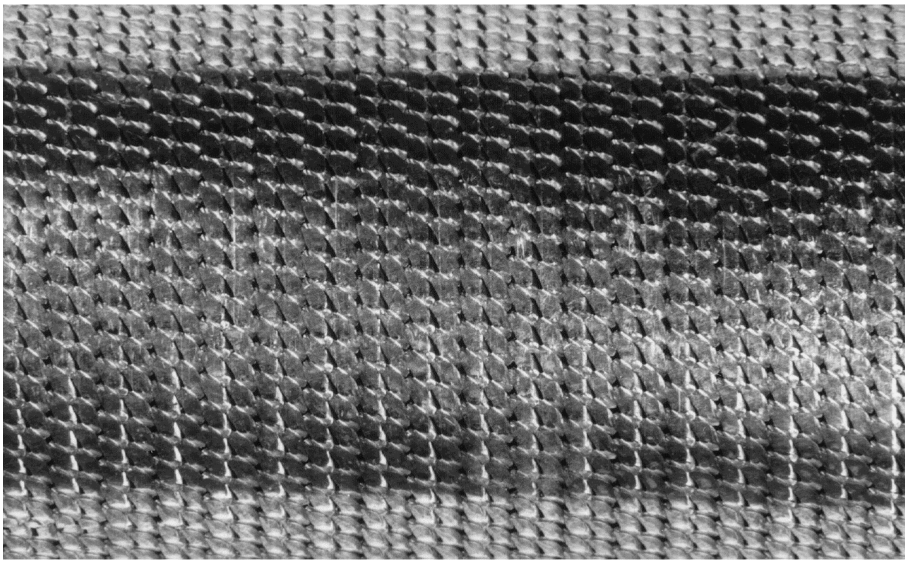

Figure 1: Magnified view of an enhanced evaporation surface

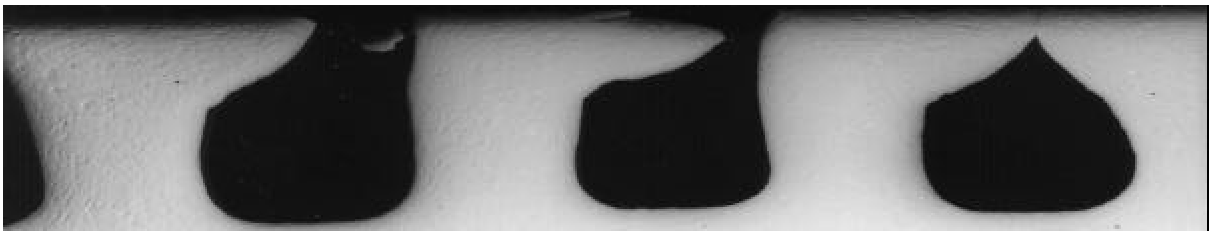

Figure 2: Cross-sectional view of the sub-surface structures

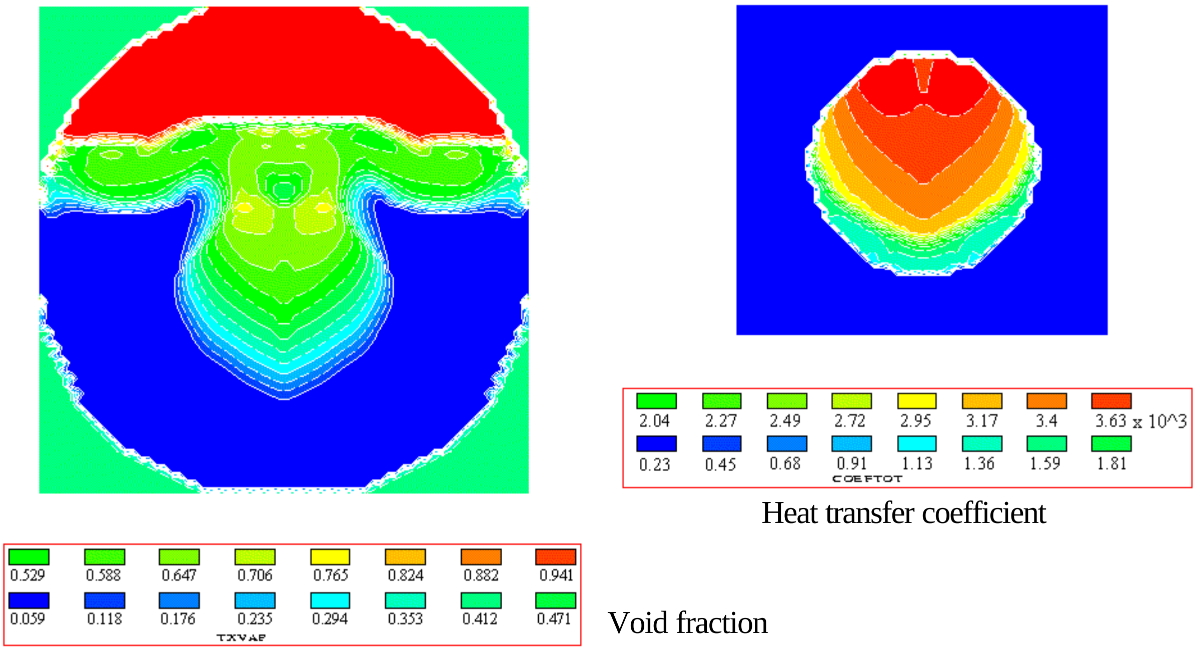

Figure 3: 2D modelling of kettle reboilers

Figure 4: Bundle during construction (CIAT factory)

Figure 5: Propane/propylene splitter (Targor plant)

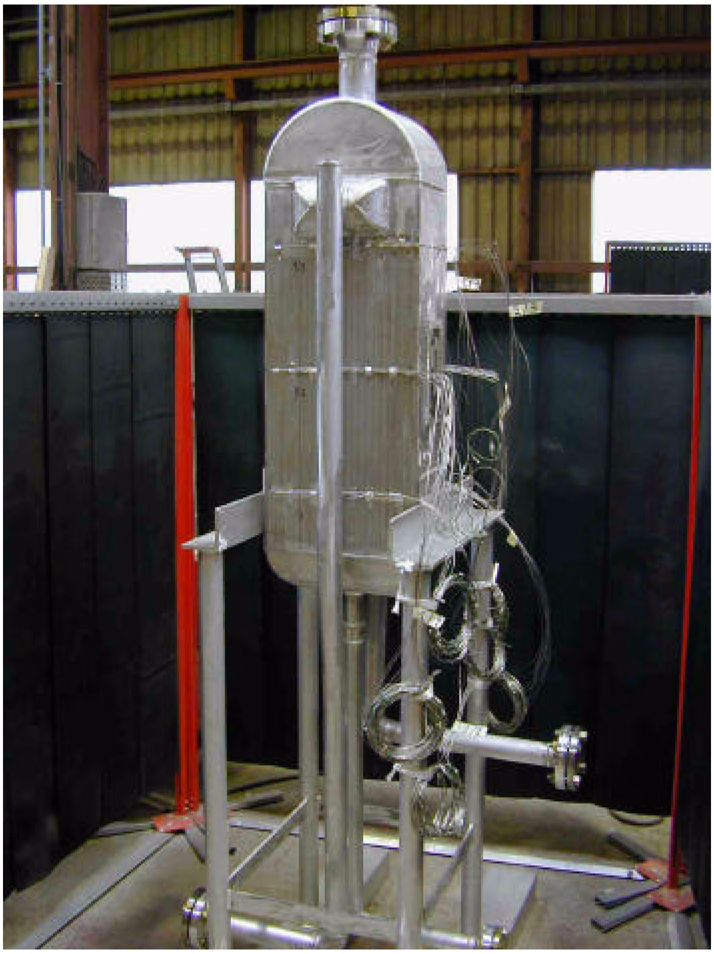

Figure 6: Compact thermosyphon reboiler