THE UHTHE/EFCC/J1 PROJECT: DESIGN, REALIZATION AND TESTING OF AN ULTRA HIGH TEMPERATURE HEAT EXCHANGER FOR INDUSTRIAL APPLICATIONS

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CONTRACT JOE3-CT95-0041

THE PUBLISHABLE FINAL REPORT

January 1, 1996 to December 31, 1997

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

I N D E X

1. ABSTRACT

In the EC, the global distribution of energy used for industrial purpose generally shows two consumption peaks: the first peak ranges from 150 °C and 250 °C, whereas the second one is around 1450 °C; at this latter temperature metallic super alloys and heat-resistant cast alloys cannot be used: the implementation of a module of an Ultra High Temperature Heat Exchanger (UHTHE) based on a modular design foreseeing the use of bayonet tubes (to be applied in the consumption peak around 1450### C, typical of the global distribution of energy for industrial purposes) allows to modernize industrial installations and to innovate high temperature technologies in industries.

New construction materials were adopted for reasons of process efficiency and reliability in service: ceramics, both advanced monolithics, at a higher development stage, and ceramic matrix composite (CMCs) were foreseen, thus exhibiting enhanced resistance against corrosion, when compared to metals.

The use of the above mentioned new materials in an industrial component like a heat exchanger needs a complete understanding of thermofluidynamics and mechanical behaviour of such component. Then, a very strong design activity was carried out, covering all the physical phenomena occurring in the component, in order to determine temperature profiles, pressure drops, velocity fields, stresses distribution, and in order to foresee the scaling/fouling of the tubes.

The project designing an UHTHE (Ultra High Temperature Heat Exchanger) started from the UHTHE process requirements and its potential use derived from an analysis of energy-related and process industry-related applications; a complete study of the shell and bayonet-tubes heat exchanger was carried out from both the thermofluidynamic and mechanical point of view. A complete set of drawings for construction concerning the metallic, the refractory conventional and advanced ceramic parts was produced. Furthermore, a supporting to the design test campaign in identified critical areas has been carried out. The project encompassed 3 technical areas:

Application & Requirements: analysis of various industry and energy related applications and definition of the UHTHE process and functional requirements

Design: the UHTHE module was designed by means of both computer codes developed ad hoc, and 3-D CFD (Computational Fluid Dynamic) and FE (Finite Element) structural commercial codes. In the final design phase, particular emphasis was given to the tube-to-tubesheet desmountable joints and to the intensification devices necessary to increase the heat exchange between the fluids

Characterization & Testing: the characterization phase was mainly devoted to bench scale tests regarding: fouling/corrosion, heat enhancing devices and joinings; in details the tests concerned:

- corrosion/fouling in coal combustion environment (in a 0.5 MW furnace);
- process intensification devices (in bench scale-tests, with cold and hot fluids);
- reliability of the tube-to-tubesheet joints (in hot pressurized tests).

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3. OBJECTIVES

There is a strong industrial need to modernize high-temperature-and-corrosive-stream-based industrial processes and energy plants, which turns into competitiveness, and lower environmental impact; this requires the availability of products with increased functionality, improved properties, reduced complexity with a lower cost.

In particular when considering the limited resources of fossil fuel such as oil or natural gas, the need for innovative clean-coal technologies is obvious. Various applications can be considered for the heat exchanger (UHTHE) and classified into two main groups: energy and industry related applications, being for the last the more promising to be considered the metallurgical, glass and chemical industries.

A significant barrier to the introduction of new components in industrial installations, although in most cases it would enhance the performance of the process, is often represented by the lack of information on reliability and durability. In addition, when new materials are concerned, such as CMCs, questions arise about design criteria, integration with conventional parts, controls.

The availability of UHTHE to be employed in high corrosive, high fouling streams is essential to promote European industries competitiveness: the industrial objectives, in the short-to-medium term, are:

- to design an efficient UHTHE (i.e.: high effectiveness, high surface-to-volume ratio, high reliability, availability, maintainability)
- to design it for high temperatures, featuring advanced ceramic materials
- to demonstrate it, in *service-representative* conditions
- to achieve cost targets which make its use cost-effective, when compared with competing technologies (existing and developing)

One of the most interesting applications in the energy field is the Externally Fired Combined Cycle (EFCC) process, whose concept is quite simple and combines the advantage of the high efficiency of gas turbine technology (currently available only for clean fuels), with the possibility to use long range available (dirty) fuels such as coal. For the realisation of this process, the availability of a high temperature heat exchanger is indispensable, where for reasons of efficiency, the temperature of the working fluids has to be as high as possible.

The UHTHE designed in the project on the base of the EFCC cycle requirements, leads to significant strategic results for the industrial partners and the European Union: The following list shows the importance for the EC to develop such technology:

- 30-40% of the primary energy consumption in the world is in industrial processes; increasing competition in most types of products calls for a modernization of processes, via more efficient, flexible, compact, environmentally friendly systems
- actual scenario, natural gas as first option for power production plants; is going to change in the 21st century; the difficulty to obtain long-term contracts for premium fuels is indicative of the uncertainty over the future availability/cost of these fuels
- developing gas turbine systems using non standard or long range, home available fuels ensures that the EC will have cost effective and environmentally sound

options to supply future power generation needs and will implement a rational use of energy in industrial processes

- generation of heat or electricity from low grade or environment waste from industries or municipalities is possible
- due to the EFCC high efficiency and low emission, a reduction of CO2 linked to the improved efficiency will be possible; competitor systems are showing limits, in terms of either efficiency, emissions or capital costs
- European utilities, industries and research centres have the capabilities to develop the enabling technologies
- financial gains can be obtained through primary energy savings
- environmental gains can be obtained through lower emission outputs
- toxic emission reduction can be obtained through improved flue gas treatment.

The objectives of the development of an UHTHE for EFCC application are characterised by peculiar design conditions:

- the use of ceramic bayonet (outer/inner) tube couples as exchanging elements, where:
    - outer tubes require: high coefficient of thermal conductivity of the used material; reliability under the thermal loads given by the temperature level and gradient; no failure under the mechanical loads as a result of the inner pressure, of different thermal expansion and of flange reactions; corrosion resistance under high temperature and vibration load inputs
    - inner tubes require: low coefficient of thermal conductivity of the used material; reliability under the thermal loads given by the temperature level and gradient
- the use of metallic materials for any other structural elements of the UHTHE
- the development of the tubesheet in a cooled sandwich design thus allowing the use of thin walled sandwich plates
- the use of the „cold end“ temperature of the air inlet for the cooling of the metallic elements in order to keep the temperature of the metallic components below the critical limits
- the development of a reliable and pressure tight connection of the ceramic tube and the metallic tubesheet, where:
    - outer tube to tubesheet joint requires high pressure sealing, up to 17 bar, at high temperatures up to 1395 °C, uncooled; a low leakage rate, about 0.1 - 2 %; a high temperature stability and positioning; no maintenance; easy assembling/ disassembling
    - inner tube to tubesheet joint requires low pressure sealing at high temperatures, up to 1300 °C; high temperature stability (see above) and positioning; no maintenance and easy assembling/disassembling
- the development of an adequate conduction of the cooling air and of an insulation system

the study of fouling and slagging phenomena on the heat exchanger tubes suggesting possible ways of minimising these undesired phenomena reducing the

thermal efficiency of heat exchangers and affecting the integrity of the mechanical devices due to corrosion, erosion or deposit on the tubes

the development of a fouling/slagging modelling post-processor to an existing combustion code is expected to be a useful tool for the specific application design

It is believed to be of strategic interest for the European society, to develop the technology required for high temperature applications where industrial, social and economic aspects justify its externally financed development due to

- the possibility for European industry to market the technology globally
- the expected employment effects in the manufacturing industry, for an instance in the market of radiant tubes for indirect heating, where the closed end tubes are very similar to the ones needed for the considered application
- the expected employment effects in the zones where the system will be installed or of potential installation of the system, agricultural, for an instance
- the improvement to be considered in public health (and the related costs), owing to the less polluting way of energy generation: the population as a whole could get improved life conditions due to the potential reduced emissions

4. TECHNICAL DESCRIPTION

<u>SYNTHESIS OF THE RESULTS ACHIEVED YEAR BY YEAR ON AN "AREA" BASE</u>

The project, organised according to the under reported breakdown structure, has developed typical technical contents linked to the various areas during two years activity.

The project main achievements in the first year's activities have been:

Area 1 (Assessment of Applications and Definition of Requirements)

- the investigation of both Industry and Energy related applications in order to assess benefits, advantages and savings arising from the UHTHE introduction in the various applications considered
- the definition of the UHTHE key process parameters and functional requirements of the considered industrial and energy related applications in order to allow the choice of the "envelope" reference conditions to be used for the Sizing/Design phase

the upgrading of the "COHEX" program, originally developed in the frame of the JOU2-CT93-0329 contract for the thermodynamic design of high temperature heat exchangers, by means of enhancing the capability of the "Flue Gas" menu composition.

Area 2 (Design)

- the definition of the conceptual design of a shell and tube 100-500 kW module design, including a database on properties and behaviour of commercial refractory linings and a preliminary drawing of the module

the implementation of an integrated (in terms of thermofluidynamic, heat transfer, mechanical, calculations) simplified (in terms of description of physical phenomena, fouling, erosion, corrosion) design code

the reference design completion, through

. the selection of the applicable process and functional "envelope" requirements

. the optimization of the module conceptual design and the sizing applied to the chosen energy application

. the sketches of the module arrangement derived from the extension of the mod ular concept to the actual mass flow rates

. the design of "reasonable (in terms of costs, effectiveness and manufacturing) Process Intensification Devices

. the design of tube to tubesheets joints, in terms of joining of the outer tube to the lower tubesheet, of the inner tube to the upper tubesheet and definition of inner to outer tube clearance

. the tubes and joints finite elements analysis, in terms of stress and reliability analysis based on given material data as well as mechanical and thermal loading conditions aiming for a fine tuning of geometry and tolerances

. the fouling/corrosion assessment, carried out by means of the development of a post-processor for slagging/fouling prediction, its validation by means of an experimental campaign, the suggestion (for fouling and corrosion reduction and clean-up systems) and modifications applied to the developed design when compared to the conceptual one

Area 3 (Characterisation & Testing):

- the finalization of the Si/SiC outer tubes and Corundum inner t ubes samples, in terms of design, number and procurement for fouling/corrosion burner rig tests, for Bench Scale Hot Tests on Process Intensification Devices, for hot pressurized tests on tube to tubesheet joints

the CMC's materials samples definiton (limited, for budgetary reasons, only to fouling/corrosion burner rig tests), supplying the campaign on monolithic samples sufficient information on the other main items (PID's and tube to tubesheet joints)

the carrying out of the first phase of the burner rig tests for fouling/corrosion assessment (fuel characterization, existing furnace adaptation to the samples, initial representative elements trials for code validation, strength and fracture tests)

the carrying out of the first phase, cold/warm Bench Scale Tests, on PID's, for their pre-selection based on consideration linked to benefits, heat exchange increase, and disadvantages, increased pressure drops

the test facility design and preparation for carrying out the hot Bench Scale Tests on pre-selected PID's

The project main achievements in the second year’s activities have been:

Area 2 (Design)

- the reference design (based on the outputs of the first year activity) optimization following some predefined steps, that is to say:

. its thermomechanical analysis, by getting - through the study of the temperature distribution in all the components of the tube-to-tubesheet joint - the verification of the thermal level of the metallic parts, with and without the presence of some modifications introduced in order to respect the maximum allowable temperature of 500 ºC

. its thermofluidynamic analysis, getting - by means of CFD FLUENT code - an evaluation of local heat transfer and pressure drop distribution near process intensification device (rings) chosen on the base of economical and functional considerations. The presence of rings outside the outer diameter of the inner tube shows significant heat transfer enhancement, to be balanced with induced pressure drops penalties by acting on ring height and pitch

. the fouling/corrosion assessment finalization through the development and application of a numerical model for particulate fouling/slagging prediction (validated by means of an experimental campaign in a pulverised coal-fired furnace), the suggestions and modifications to be taken into account for fouling and corrosion reduction and the clean-up systems to be applied to the design in comparison to the reference one (such as for an instance recommendations for tube pitchings, bank arrangements, ash hopper design, coal ash quality versus UHTHE inlet temperatures...)

- the final design compl etion, through

  . the “optimum” modification of the tube to tubesheet joint (individual clamping plate with a detailed mounting procedure)

  . the modification of outer tube shape at open ends (according to the spacer tube increased dimensions)

  . the subdivision of the UHTHE into thermal zones (function of the flue gas temperature, particle loading and coal characteristics)

  . the definition of baffles and sootblowers arrangement

  . the definition of the UHTHE final dimensions (increased due to the presence of cavities for sootblowers and of bottom hopper for ash removal)

  . the analysis (in terms of modules to be added to the “ clean”, as oversizing to take into account the effect of fouling) of the “fouled” heat exchanger performances deterioration

  . the mechanical calculations on the external pressure vessel, in particular in the zone of the cold nozzle connection and of the upper flange connection, the influence of the presence of lateral stiffeners

Area 3 (Characterisation & Testing):

- the CMC's materials samples (square plates) supply for fouling/corrosion burner rig tests on typical European coals

the carrying out of the second phase of the burner rig tests for fouling/slagging assessment on advanced monolithic materials and of the third phase for corrosion assessment on CMC plates

the completion of cold/warm bench scale tests on PIDs, for their pre-selection based on a trade-off between heat exchange enhancement and increased pressure drops

the carrying out the hot bench scale tests on pre-selected PIDs

the completion of hot pressurized tests on tube to tubesheet joints in order to determine leakages levels and verify their acceptability

5. RESULTS AND CONCLUSIONS

In terms of efficient use of energy, the necessity for higher process temperatures is obvious, this concerning not only the generation of electrical energy, but also many other industrial processes.

The application fields were assessed in terms of benefit linked to the introduction of an high temperature heat exchanger and the possible range of application and it was found that the most promising field of application was generation of electrical energy: several possible processes were investigated. From those, the Externally Fired Combined Cycle process (EFCC) was selected as reference application, because it is a quite simple process, that suffers most of the lack of high temperature heat exchangers.

In order to obtain high efficiency, the peak temperature of the process was chosen as 1400°C, being the limit for monolithic SiSiC tubes. Ongoing to even higher temperatures, advanced ceramic compound materials could be employed, where, however, the current market situation for those materials is such, that even for development purposes the costs are by far too high. Thus, the development focused on materials and design concepts, that are readily available at competitive prices.

The design of an ultra high temperature heat exchanger was based on ceramic monolithic SiSiC tubes bayonet tubes (avoiding completely the problem of differential thermal expansion) as exchanging elements. This design applied to the EFCC process led to several new solutions, concerning both, the concetpual approach and the technical details to be solved. During the ongoing development, the external shape of the heat exchanger changed from typically circular (pressure vessel) design to a rectangular shape with a semi-circular shape for the high pressure part.

A design concept was found, that combines the active heat exchanger area made of ceramic materials with the more conventional solution of metallic tubesheets. An internal cooling system, based on the cold-end inlet temperature of the cold side fluid was adopted, in order to keep the temperature of the metallic components below the critical limits.

The cooling of the tubesheets and the static requirements as a pressure carrying wall between the high air pressure and the low flue-gas pressure, led to a sandwich design, which allows the use of thin walled sandwich plates. The cooling fluid can then be conducted between the sandwich covers. The hot gas facing components, however, are protected against thermal or corrossion by means of ceramical refractory/insulation layers.

When using the general concept described above, the problem of joining ceramic tubes with metallic tubesheets had to be solved. Several design concepts of this detail were proposed and discussed amongst the partners. Finally, a solution was worked out and tested. In the first approach, the tube flanges broke under the conditions required for a gas-tight connection. On the basis of this experience the connection geometry was slightly changed. The modification led to a reliable and gas tight connection, that proved its feasability under cold and hot conditions.
The actual state is, that the design of the heat exchanger is available in terms of drawings and technical detail-descriptions; the experience of cold and hot tests during the current programme showed, however, that a practical prototype testing phase is indispensable, therefore the step forward required is the construction and test of an (possibly downsized) heat exchanger module under realistic conditions: for an instance aspects of fouling/corrosion behaviour cannot be assessed by theoretical work solely.

6. EXPLOITATION PLANS

Market and potential for exploitation

All potential direct applications of the project were considered in the Project Task "Assessment of Applications"; additional possibilities may arise for indirect applications via technology transfer, where, at this stage of development, it is likely to find more easily a market in industrial applications (iron, chemical.... industries) and small CHP units rather than in large energy pruduction ones.

It is typically the case of thermal components for high temperature applications: ceramic products use increases continuously for all temperature ranges and the application know-how for the wide range of materials is used to produce industrial burners, recuperators and other high temperature components of silicon carbide and various ceramic materials due to the affordable results get on conservation, longer burner component life and reduction of noxious by-products of combustion.

In the energy field, due to the high capital cost of the UHTHE, even if a functional analysis of the project has not yet been performed, only companies really interested can be regarded as potential users of this advanced technology: an information package on the characteristics of the process and on the peculiar technologic aspects can also be issued when constructive details of UHTHE and auxiliary devices will be available.

In the development of the programme considerable importance is also devoted to new solid fuels characterized by high slagging and fouling: this is especially important when considering unusual ones such as pulverised sewage sludge, which is becoming more viable as an alternative fuel. Its combustion performance is similar to that of lignite, with almost half of its mass consisting of ash. Assuming that only when more precise cost-benefit analyses will be available, area and potential market study can be performed: countries with high coal reservoir or interested on fossil fuel strategic use for energy production, can be indicated as potential users.

Ansaldo's strategy is devoting specific attention to some of the deliverables of the project, which may be of wider interest than that directly addressed in the present one (i.e.: spin-offs to other products). Among these:

- design tools for high temperature components (i.e.: computer codes, such as BayCHE)
- sealing/joints technologies
- requirement for coatings of CMCs
- augmenting devices for intensifying heat transfer processes

Within the Ansaldo group, a direct exploitation of results is foreseen, by appropriately transferring the results to Ansaldo Energia active in the power generation business and in industrial applications/cogeneration.

Balcke-Durr (BD) is willing to exploit the results of the development within the field of ceramic heat exchangers. The company is well established in the market of heat exchangers and will be interested to participate with state of the art solutions in the growing field of rational use of energy. The experience of cold and hot tests during the current programme showed, however, that a practical prototype testing phase is indispensable.

ENEA, interested in using of ceramic materials and studying heat transfer surfaces in compact heat exchangers, is expecting to derive meaningful improvements in the

- design and thermomechanical analysis of ceramic components
- design and thermoanalysis of “mixed” (metallic and ceramic) components, very difficult due to different mechanical properties of materials, especially the thermal expansion
- study of the heat transfer augmentation devices inside and outside the bayonet tubes in the UHTHE module, playing a very important role in the application

Schunk Ingenieurkeramik is willing to exploit its tubes in the field of ceramic heat exchangers. The company has been developing and producing advanced ceramics based on oxide and non-oxide materials for over 10 years in the field of high temperature applications for furnace constructions and producers of burners. The results of testing on extruded corundum and casted siliconised silicon carbide tubes have been satisfactory and good chances are predicted in creating new technological solutions for energy systems. .

On this base various steps are foreseen (with the participation of other partners) in order to get to the whole product (heat exchanger) exploitation:

- prototype construction (Ansaldo and BD for component construction, Schunk for tubes manufacturing): from late 1998 to late 1999
- testing in a coal fired test facility (ENEL/Ansaldo for the test facility adaptation, BD, ENEA and Schunk for the test campaign carrying out): from late 1999 to end 2000
- product industrialisation (Ansaldo, BD, and Schunk): from 2001 to en d 2002
- industrial field commercialisation (partnership TBD): from 2003 to....
- energy field commercialisation (partnership TBD) from 2005 to......

In addition GRETh and CSM built devoted high temperature experimental loops to carry out specific pressurized test campaigns; they were finalised to verify respectively, on bayonet tubes assemblies, the leakage levels of the developed tube-to-tubesheet joint and the reasonable possibility of adopting process intensification devices in order to reduce the number of expensive ceramic exchanging elements. These testing loops are now available or improvable to follow new testing specifications.

CINAR s.a. existing combustion modelling codes (extensively used to model and design both furnaces, boilers ...), have been further improved by a fouling/slagging modelling post-processor believed of great interest in various industrial applications. It is expected to be used during the design phase of heat exchangers, furnaces, combustion chambers..., to minimize slagging / fouling phenomena and to determine the expected operational time between two successive cleanings of the devices.

Dissemination

The rate and level of detail of information dissemination will reflect the commercial sensitivity of the information and the estimated time to market; common tools for exploitation of results will be used, to advance promotion of the UHTHE technology to a large academic and industrial audience, such as:

- reports and publication of technical articles on specialized and internation ally recognized journals
- attendance at international conferences

- applications to be submitted to national Governments for support to follow up R&D efforts

7. PHOTOGRAPHS AND FIGURES

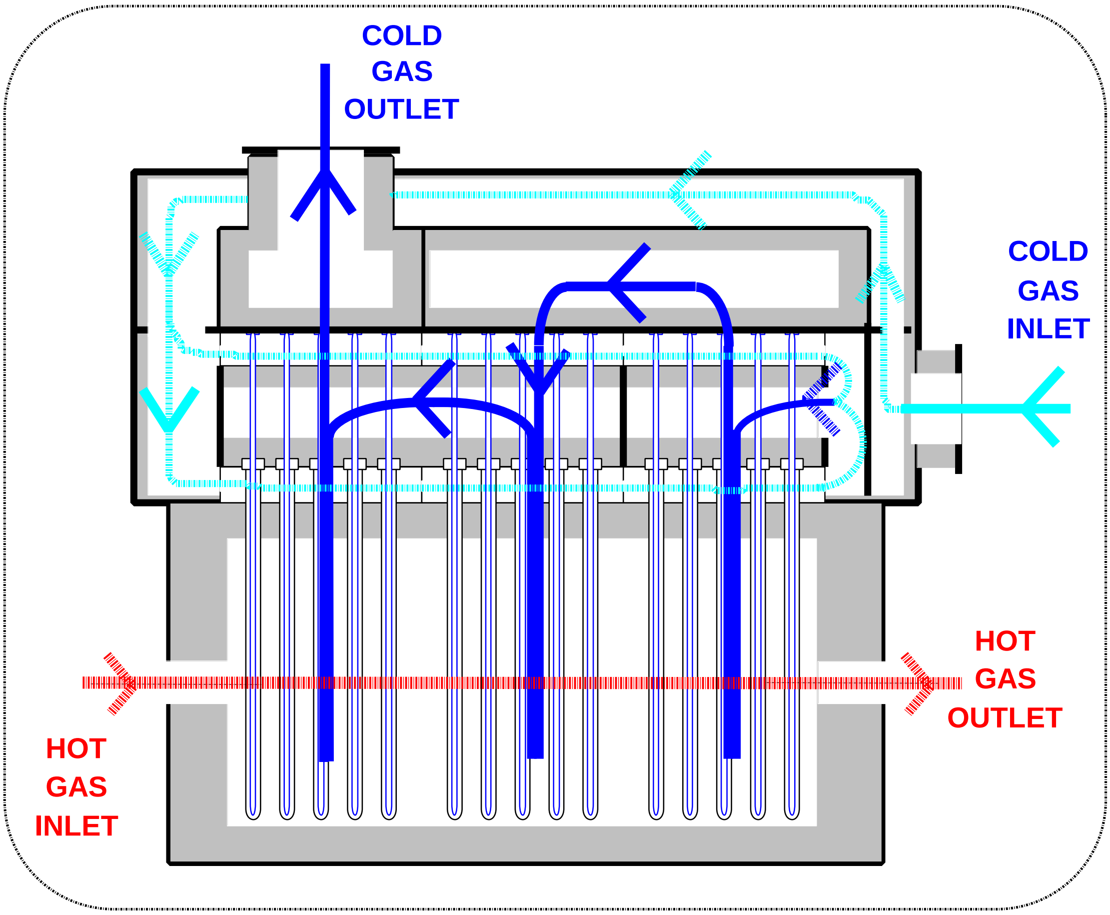

FIGURE 1: Schematic of the heat exchanger final design

FIGURE 2: Heat exchanger module arrangement in the final design

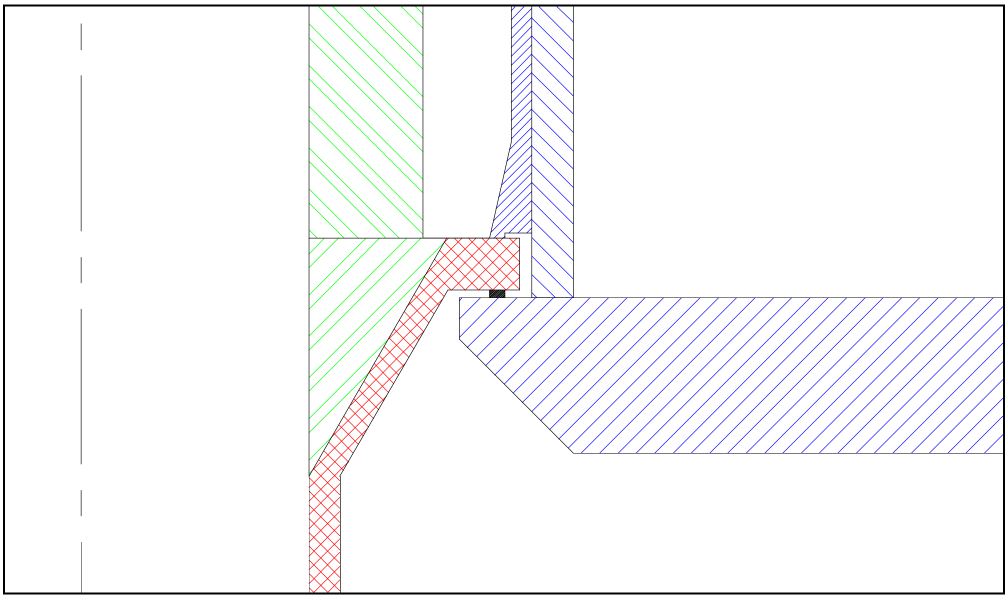

FIGURE 3: Schematic representation of the tube-to-tobesheet final joint