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Thermomechanical fatigue life prediction of 316L compact heat exchanger

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ABSTRACT

Compact welded heat exchangers are designed to be used in severe operating conditions (temperature, pressure, aggressive fluid, etc.). Thus fatigue failure can be observed after large cyclic strain due to thermomechanical cyclic loads. In this paper, a 316L stainless steel structure solicited in the (extremely) low cycle fatigue regime is analyzed through a multi-scale approach. A finite element analysis method has been developed and correlated to experiments. The thermo-elastic response of the heat exchanger to thermal cycling of various amplitudes has been firstly investigated. The stress concentration locations are identified and the local thermo-elastic stored energy on these points is calculated. By the use of a combined isotropic/kinematic hardening previously determined by alternated bending tests, these data are then used in a micromechanic approach. It consists in the consideration of the material elastic-plastic behavior under uniaxial mechanical solicitation. Based on energy equivalence, a local nonlinear description is so adopted to an expected equivalent strain amplitude. This estimation is used to predict the lifetime of the heat exchangers through an adapted rule relying this deformation to cycle number to failure through the Coffin Manson law. The methodology, simple to handle, is thought to improve the design of heat exchangers depending on their operating conditions.

1. Introduction

1.1. State of the art

Fatigue has been widely studied from a general and scientific point of view during last decades. Some applications received also a lot of attention such as in bearings or structural materials for aeronautics [1,2]. However, surprisingly fatigue in the case of heat exchanger has been barely addressed. Most of the recent references concerning the failure analysis of exchanger deal with a metallurgical approach in order to mainly identify the damage mechanics involved in industrial problems [3,4,5]. In these studies, the fracture of heat exchanger has been associated to thermal fatigue coupled to microstructural feature such as the presence of defects (i.e. sulphides in [4]). It is necessary to come back to the 90's to find some numerical approach of a heat exchanger failure. Ferguson and Gullapalli [6] suggested a way to include a fatigue model in a thermo-elastic analysis of a gas fired heat exchanger. This leads to a possible estimation of the fatigue life of this type of exchanger.

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In the same way, Nakaoka, Nakagawa and Mitsuhashi [7] have worked on the evaluation of fatigue strength of plate-fib heat exchanger under cyclic thermal loading. Thermal fatigue having also supposed to be involved, a coarse linear FE model was used together with fatigue test data. The strain is calculated probably with a pure elastic behavior of the materials and compared to experimental results giving the number of cycles to fracture according to the strain amplitude imposed during the test. This comparison is used to determine the fatigue life of the heat exchanger. Even if the fatigue life seems to be correctly predicted by this approach, it is clearly very coarse as it does not take into account the plastic behavior of the materials and considered only a uniaxial loading although it is clearly not the case in the real case.

1.2. Description of the problem

The compact heat exchanger system considered here consists in the assembly of two main parts. The core is firstly constituted of thin plates stack welded together alternatively on each side, allowing two fluids to transfer heat by crossing themselves. The frame part then envelops the whole core with thick panels (Fig. 1).

The relevance of this study is to understand the appearance of leaks observed in a zone situated between the core and the frame part due to brittle fracture. In operating conditions, compact heat exchangers are solicited by cyclic thermal gradient, due to occasional start up and shut down. Under high fluid temperature difference, these ones are subjected to small numbers of large cyclic strains until failure caused by thermal behavior differences between both core and frame part. During heating (start-up) in example, thin plate (1 mm thickness in the case of the study) pack will be submitted to a thermal gradient very sharp, so a material expansion almost instantaneous, when frame panels (reaching a thickness of 110 mm) is supposed to experience a lower temperature rise, confining the core. Concerning cooling, the inverse phenomenon is observable.

Thermal fatigue failure appearing to be involved, the objective of this study is firstly to analyse the macroscopic stress distribution on the heat exchanger finite element model. In second approach, once the failure mode is confirmed, a damage criterion will be introduced in order to be able to suggest a temperature range certifying safety during a certain time.

2. From an elastic strain energy density to an equivalent plastic strain amplitude

2.1. Background

One of the first requirements is to point out stress concentration localization by a sufficient accurate linear finite element description of the heat exchanger. The structure representing a complex geometry to take into account, the idea is to begin step by step at the mesoscopic scale with the study of the plate pack.

Plates are made with AISI 316L austenitic stainless steel whose basic chemical composition is 16–18%Cr, 10–14%Ni, 2–3%Mo. Mo addition is specially important to increase localized corrosion resistance in aggressive environments. As shown in Fig. 2 plates are constituted of a central corrugated zone considered by a linear orthotropic material model and a finer smooth zone on the borders. The mechanical properties of the orthotropic material are presented in Table 1.

It should be specified that elastic material of the laminated smooth zone corresponds to E_1 and υ_{13} in Table 1. It is worth noting that E_2 has been calculated using finite elements on tensile test with a corrugated sample.

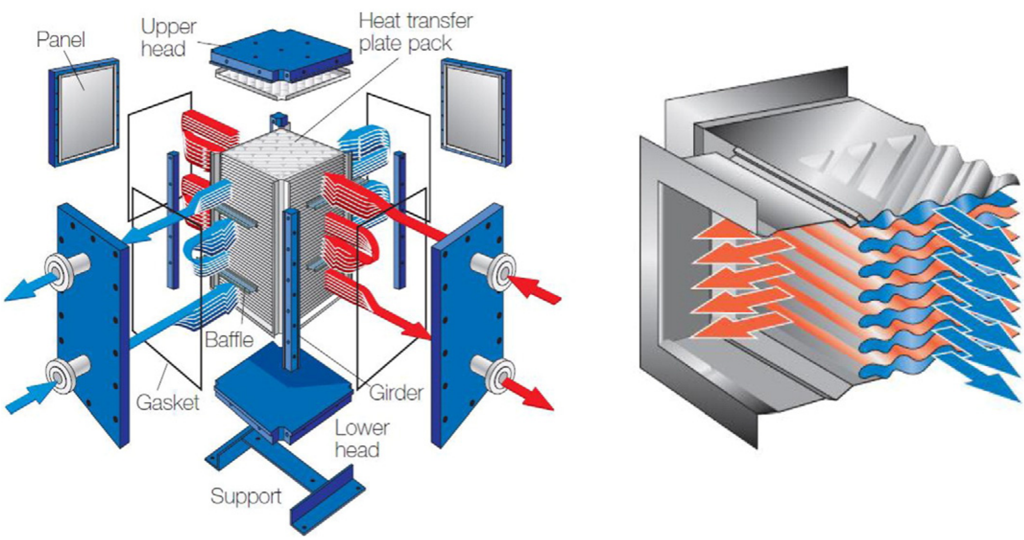

Fig. 1. Thermal circuit within the exchanger.