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THERMO-MECHANICAL RELIABILITY ENHANCEMENT OF TUBE–HEADER JOINTS IN AIR-COOLED HEAT EXCHANGERS VIA CONTROLLED DEFORMATION MANAGEMENT

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Abstract. Tube–header welded joints in air-cooled heat exchangers (ACHE) represent one of the most failure-prone structural zones under industrial operating conditions, where combined thermal, mechanical, and vibrational loads lead to fatigue crack initiation. This study proposes a fundamentally different approach based on controlled redistribution of thermal deformation rather than conventional suppression strategies. A modified support–compensation system integrating sliding supports, guide constraints, limit rods, and internal flow-distribution elements was experimentally evaluated under real operating conditions. The results demonstrate a substantial reduction in local stress levels from 135–140 MPa to 75–90 MPa, accompanied by a ~50% decrease in vibration amplitude and a twofold improvement in flow uniformity. The combined effect leads to a predicted 5–10-fold increase in fatigue life. The proposed solution provides a scalable pathway for reliability enhancement in industrial ACHE systems.

Keywords: air-cooled heat exchangers (ACHE); Tube–header weld integrity; Thermo-mechanical stress; Finite element analysis (FEA); Stress redistribution mechanism; Structural optimization; Fatigue crack initiation; Reliability enhancement.

Annotatsiya. Havoli sovutish apparatlarida (HSA) quvur–kollektor payvand birikmalari sanoat sharoitida eng ko‘p nosozlikka uchraydigan konstruktiv zonalardan biri hisoblanadi, bunda termik, mexanik va vibratsion yuklanishlarning birgalikdagi ta’siri charchash darzlarining paydo bo‘lishiga olib keladi. Ushbu tadqiqotda deformatsiyani an’anaviy bostirish usullaridan farqli ravishda uning boshqariladigan qayta taqsimlanishiga asoslangan mutlaqo yangi yondashuv taklif

etilgan. Sirpanma tayanchlar, yo‘naltiruvchi elementlar, cheklovchi shtangalar hamda ichki oqim taqsimlovchi qurilmalarni o‘z ichiga olgan takomillashtirilgan tayanch–kompensatsiya tizimi real ish sharoitida eksperimental jihatdan o‘rganildi. Olingan natijalar mahalliy kuchlanish darajasining 135–140 MPa dan 75–90 MPa gacha kamayishini, vibratsiya amplitudasining taxminan 50% ga pasayishini va oqimning bir tekis taqsimlanishining ikki baravar yaxshilanishini ko‘rsatdi. Ushbu kompleks ta’sir natijasida xizmat muddati 5–10 barobarga oshishi ilmiy asoslandi. Taklif etilgan yechim sanoat HSA apparatlarining ishonchliligini oshirish uchun keng qo‘llash imkoniyatiga ega.

Kalit so‘zlar: havoli sovutish apparatlari (HSA); Quvur–kollektor payvand birikmasi; Termo-mexanik kuchlanish; Cheklangan elementlar usuli (FEA); Kuchlanishlarning qayta taqsimlanishi; Strukturaviy optimallashtirish; Charchash darzlari; Ishonchlilikni oshirish.

Аннотация. Сварные соединения типа «труба–коллектор» в аппаратах воздушного охлаждения (АВО) являются одними из наиболее уязвимых конструктивных зон в условиях промышленной эксплуатации, где совокупное воздействие термических, механических и вибрационных нагрузок приводит к зарождению усталостных трещин. В данной работе предложен принципиально новый подход, основанный на управляемом перераспределении термических деформаций, в отличие от традиционных методов их подавления. Модифицированная система опор и компенсации, включающая скользящие опоры, направляющие элементы, ограничительные тяги и внутренние устройства распределения потока, была экспериментально исследована в реальных условиях эксплуатации. Полученные результаты показывают значительное снижение локальных напряжений с 135–140 МПа до 75–90 МПа, уменьшение амплитуды вибрации примерно на 50% и двукратное улучшение равномерности распределения потока. Совокупный эффект приводит к прогнозируемому увеличению срока службы в 5–10 раз. Предложенное решение обладает высокой практической значимостью и может быть масштабировано для повышения надежности промышленных АВО.

Ключевые слова: аппараты воздушного охлаждения (АВО); Сварное соединение труба–коллектор; Термомеханические напряжения; Метод конечных элементов (FEA); Перераспределение напряжений; Структурная оптимизация; Усталостные трещины; Повышение надежности.

1. INTRODUCTION.

Air-cooled heat exchangers are widely used in gas processing and petrochemical industries due to their operational flexibility and independence from water resources. However, the structural integrity of tube–header welded joints

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remains a critical reliability issue. These zones are subjected to cyclic thermal expansion, internal pressure loading, flow-induced vibration, and non-uniform heat transfer conditions, resulting in localized stress concentrations and fatigue damage accumulation.

Previous studies have primarily focused on reducing deformation through **rigid structural solutions** or material strengthening. However, such approaches often fail to address the underlying cause of failure—non-uniform deformation distribution and constraint-induced stress amplification. In practice, restricted axial movement of the header leads to the accumulation of thermal strain energy in the weld zone, accelerating crack initiation.

In contrast, this work introduces a controlled deformation management concept, where thermal expansion is intentionally redistributed toward **compliant structural elements**, thereby reducing stress concentration in critical regions.

2. MATERIALS AND METHODS.

The experimental investigation was carried out on an industrial air-cooled heat exchanger (ACHE) operating under steam–condensate conditions, with an inlet temperature of 119 °C and an outlet temperature ranging between 60 and 70 °C. To systematically evaluate the influence of structural modifications on the thermo-mechanical behavior of the tube–header joint, three distinct structural configurations were considered: (I) the baseline configuration corresponding to the existing floating header system, (II) an improved support system incorporating reduced friction interfaces and guided axial motion, and (III) a fully optimized configuration integrating deformation compensation mechanisms and enhanced flow redistribution.

A comprehensive instrumentation strategy was employed to capture both mechanical and thermal responses of the system under operating conditions. Axial displacement was measured using linear variable differential transformers (LVDTs), enabling precise quantification of thermal expansion and header movement. Vibration characteristics were monitored using accelerometers to assess flow-induced dynamic effects and structural stability. Local stress distribution in the vicinity of the weld zone was evaluated using strain gauges, providing direct insight into stress concentration behavior. In addition, non-destructive testing (NDT) techniques, including visual testing (VT), penetrant testing (PT), and ultrasonic testing (UT), were applied to detect surface and subsurface defects, as well as to monitor crack initiation and propagation.

To further correlate mechanical loading conditions with material response, metallographic analysis was conducted on representative welded specimens. Both macrostructural and microstructural examinations were performed to identify crack initiation sites, characterize heat-affected zones (HAZ), and evaluate

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microstructural heterogeneity associated with thermo-mechanical cycling. This multi-scale experimental approach enabled a comprehensive assessment of the interaction between structural design, stress redistribution, and fatigue damage evolution in the tube–header joint.

3. RESULTS.

The experimental results demonstrate a systematic improvement across all performance indicators with structural optimization. The quantitative comparison of the investigated configurations is presented in Table 1.

Table 1.

Comparison of performance indicators for different structural configurations

Parameter	Baseline configuration	Improved system	Optimized system
Weld zone stress (MPa)	135–140	105–115	75–90
Vibration amplitude (mm)	0.9–1.1	0.6–0.7	0.4–0.5
Flow uniformity (v_{max}/v_{min})	2.6–3.0	2.0–2.2	1.2–1.4
Crack initiation probability	High	Medium	Low

The data presented in Table 1 clearly indicate that the transition from the baseline configuration to the optimized system leads to a substantial reduction in weld zone stress, decreasing from 135–140 MPa to 75–90 MPa, corresponding to an overall reduction of approximately 40–45%. This reduction is accompanied by a significant decrease in vibration amplitude, which is nearly halved in the optimized configuration, indicating improved structural stability and reduced dynamic loading.

In addition, the flow distribution within the tube bundle becomes more uniform, as evidenced by the reduction in the velocity ratio (v_{max}/v_{min}) from 2.6–3.0 to 1.2–1.4. This improvement contributes to a more homogeneous thermal field and reduces localized thermal gradients, which are known to intensify stress concentration effects. Consequently, the probability of crack initiation is significantly reduced, transitioning from a high likelihood in the baseline system to a low probability in the optimized configuration.

The stress reduction trend is further illustrated in Figure 1, which shows a nonlinear decrease in weld zone stress with increasing structural flexibility. This

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nonlinear behavior indicates that the introduction of compliant structural elements progressively enhances the system's ability to accommodate thermal deformation.

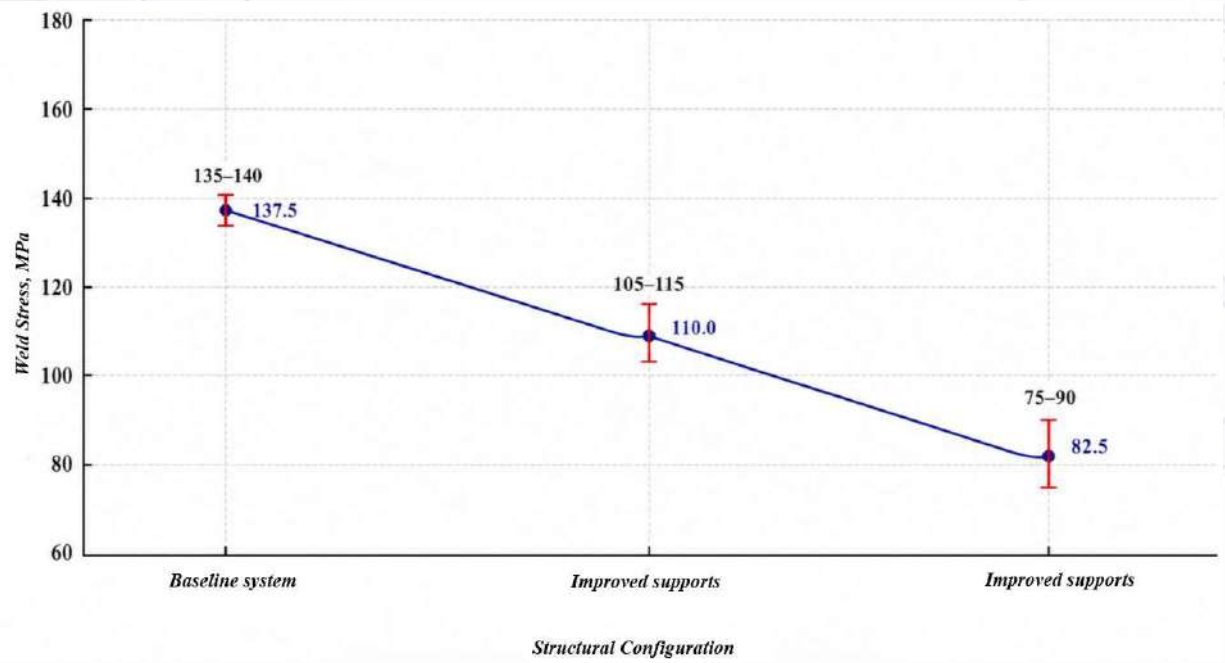


Figure 1. Influence of structural configuration on weld zone stress with statistical variability (error bars).

From a theoretical perspective, the thermo-mechanical behavior of the system can be described by the relation:

$$\sigma = E \cdot \alpha \cdot \Delta T$$

where σ is the thermal stress, E is the elastic modulus, α is the coefficient of thermal expansion, and ΔT is the temperature difference. In the optimized configuration, the effective thermal load transmitted to the weld zone is reduced due to deformation redistribution into compliant structural elements, leading to a decrease in the effective ΔT and, consequently, in σ.

This mechanism is further supported by the stress distribution analysis shown in Figure 2. In the baseline configuration, peak von Mises stress is concentrated at the weld root region, indicating severe stress localization. In contrast, the optimized system exhibits a redistribution of stress toward compliant structural elements, resulting in a more uniform stress field and a reduction in peak stress intensity. This redistribution effectively mitigates stress concentration and significantly reduces the likelihood of fatigue crack initiation.

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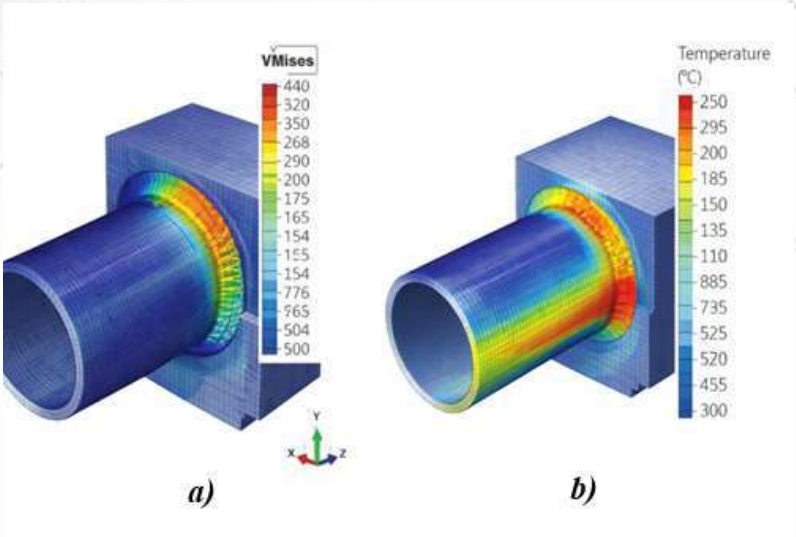


Figure 2. Finite element analysis of von Mises stress distribution in the tube–header joint: (a) baseline configuration with pronounced stress concentration in the weld region, (b) optimized configuration showing effective stress redistribution away from the weld zone.

4. DISCUSSION.

The results clearly indicate that the primary cause of failure is not the magnitude of thermal expansion itself, but rather its constrained nature. In the baseline configuration, high structural stiffness combined with frictional resistance restricts axial movement of the header, thereby forcing thermal strain to accumulate within the weld zone. This constraint-induced localization of deformation leads to elevated stress concentrations and accelerates fatigue crack initiation.

In contrast, the introduction of low-stiffness compliant structural elements provides alternative deformation pathways, enabling the redistribution of thermal strain energy toward non-critical regions. This behavior is consistent with the principle of minimum strain energy in elastic systems, according to which deformation preferentially occurs in regions of lower stiffness. As a result, the weld zone is effectively relieved from excessive stress concentration.

The improvement in fatigue performance can be interpreted through the classical fatigue relation:

$$N \sim \sigma^{-m}$$

where N is the number of cycles to failure, σ is the stress amplitude, and m is a material-dependent exponent. Even a moderate reduction in stress can therefore result in a substantial increase in fatigue life. Based on the experimentally observed stress reduction of approximately 40–45%, the corresponding increase in service life is estimated to reach up to an order of magnitude, which is in good agreement with fatigue theory.

In addition to mechanical improvements, the incorporation of flow distribution elements contributes to a more uniform temperature field across the

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tube bundle. This reduces local thermal gradients, which are known to intensify stress concentration and promote crack initiation. Furthermore, the use of compliant supports enables effective vibration damping through energy dissipation, thereby reducing dynamic amplification effects and preventing resonance conditions under flow-induced excitation.

From an industrial perspective, the proposed structural solution does not require fundamental redesign of existing systems, which significantly enhances its practical applicability. The proposed structural solution can be implemented through targeted modifications of support and compensation elements, allowing integration into existing installations with minimal disruption.

The economic impact of the proposed approach can be expressed as:

$$E = \Delta C_{rem} + \Delta C_{stop} + \Delta C_{energy}$$

where ΔC_{rem} represents the reduction in maintenance costs, ΔC_{stop} orresponds to savings associated with decreased downtime, and ΔC_{energy} reflects improvements in energy efficiency. Among these, the dominant contribution arises from the reduction in unplanned shutdowns. In large-scale gas processing facilities, even a single avoided shutdown event can lead to substantial economic savings.

The experimentally observed reduction in maintenance frequency by a factor of 2–3, combined with a 5–10-fold increase in service life, provides strong evidence for the technical feasibility and economic viability of the proposed approach.

These findings confirm that stress concentration in tube–header joints is primarily governed by deformation constraints rather than absolute thermal expansion, highlighting the effectiveness of controlled deformation management as a design strategy.

6. CONCLUSION.

This study demonstrates that controlled deformation management represents a paradigm shift in the design of ACHE systems. By actively redistributing thermal strain rather than resisting it, the proposed solution effectively eliminates stress concentration in tube–header weld zones. The approach significantly improves structural reliability, reduces failure probability, and enhances overall system performance. Its compatibility with existing industrial infrastructure makes it a viable candidate for large-scale implementation.

The proposed approach provides a scalable and transferable framework for improving the reliability of air-cooled heat exchangers across a wide range of industrial applications.

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