A Review: Distortion Patterns during Fabrication of Header-Box of Air-Cooled Heat Exchanger

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***Abstract* - This research work paves the way to explore new avenues in existing and ongoing groundwork in the field of heat exchangers. There is a dire need to address the issues related to air-cooled heat exchangers used in chemicals and energy industry. The distortions found in fully manufactured rectangular/plug header-boxes and flange-type bonnet headers can be adverse. They need to be monitored and resolved. Proper diagnosis throughout their processing and testing only can determine the root cause. This is usually done by non-destructive testing methods. Here a thorough study of the system is presented. An organized approach for the same is also proposed to eliminate the defects.**

I. Introduction

We study specialized subjects that comprise, or are related to, advancements in the discipline of manufacturing. However, not every subject-matter can be taught within the scope of curriculum prescribed. Fabrication, and in particular, assembly and welding are fields that ought to be delved into since they too deal with modern technology. It becomes, therefore, de rigueur to explore and exploit their harnesses.

Similarly, another indispensable subject that is an integral part of any validation of veracity in research is testing. This thesis aims at performing the aforementioned and monitoring the same to validate the theme.

Air-cooled heat exchangers are used extensively in petrochemical industry (hydrocarbon processing industry) [1]. Different manufacturers fabricate and supply them to their clients. GEI Industrial Systems Ltd had forayed into the manufacturing of air-cooled heat exchangers antedating its rival counterparts in the country and is currently predominating the market [2]. It utilizes advance manufacturing facilities as well as quality testing systems [3]. Being a major contributor to organizations dealing with energy and chemicals in India and offshore [4], GEI has managed to progress in tandem with oil & gas and power industry [5]. Being a self-sufficient trendsetter, it has always managed to ensure quality to the customer.

Of late, GEI has been facing an issue of distortion in the header-boxes (rectangular box-type alias plug-type header and flange-type bonnet/cover header) made of carbon-steel and stainless-steel of air-cooled heat exchangers. Testing and monitoring for these has, therefore, become imperative.

In coherence with this, experimentation, monitoring, and analysis also serve the purpose when it comes to research. Accordingly, the work here is proposed and presented.

A. Manufacturing Aspects of Heat Exchangers:

Typically, manufacturers utilize fabrication methods to produce ACHE's. Here, they resort to GTAW and SAW for weld-joining headers to the tube-bundles with considerable precision where other assembly methods such as bolts or rivets cannot be used. Finning-machines [6] can generate distinct profiles of fins that are consequentially soldered or brazed to the tubes. Finally, these are tested and shipped.

B. Heat Exchangers:

A heat exchanger is a piece of equipment that efficiently and effectively transfers heat from one medium to another.

Heat exchangers are an essential part of any process or equipment; be it an industry or a machine.

1). Types of Heat Exchangers: - In general, heat-exchangers can be attempted to classify as was done by Shah et al. [7] and even by Thulukkanam [8]. Heat exchangers can be classified on the basis of construction as tubular or plate type heat exchanger; or even as extended surface exchangers and regenerative heat exchangers. Further, based on transfer process, heat exchangers are of direct contact or indirect contact-types. This is in a broader sense. A detailed unravelling is illustrated ahead.

The same can be said of header-boxes and fins. However, manufacturers have their own configurations. For example, GEA [9] specializes in ACHE's and boasts of its own design of headers. Whereas, Amercool Manufacturing Inc. [10] specifies fan and exhaust details for commercial installations. E.g., a three-way comparison: 'G'-type groove fins at GEI Industrial Systems [11] versus L-footing heat exchanger from petrochemical industry ancillary [12] versus only rectangular and annular fins found in academic texts.

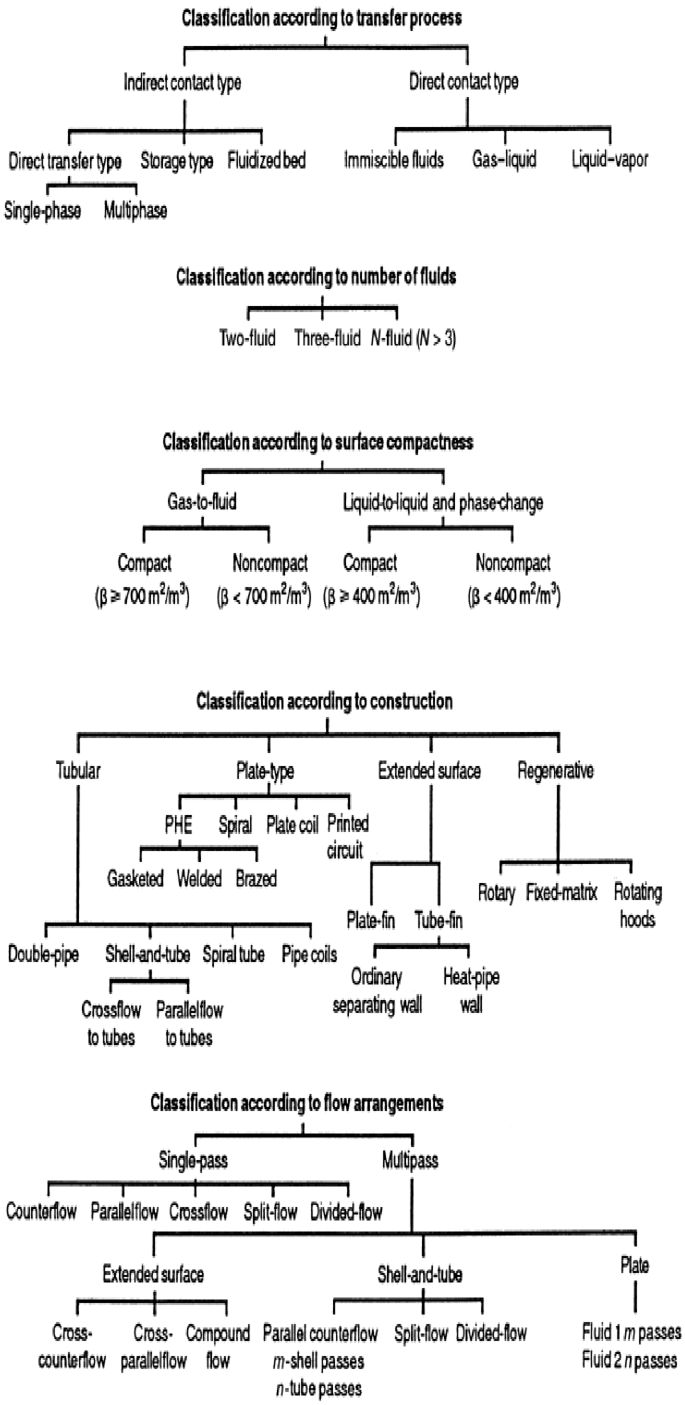

Figure 1. Classification of heat exchangers

2). Heat Exchangers in Petrochemical Industries: - Heat exchangers are used extensively in large scale petroleum industry for cooling and heating purposes. Their selection largely depends on the process and other properties [13].

In general, various functions performed by these are [14]:

- Condensation of solvents and multiple-material mixtures
- Cooling / Heating of reactors and production containers
- Cooling and heating of intermediate products
- Cooling of hydrocarbons
- Cooling of water circuits
- Benzene / Benzene heat recovery
- Heat recovery within petrochemical processes

Besides, in a unique application of Ambient Air Heater developed by GEI [11], at 5 MMTPA regasification terminal of Petronet LNG Ltd., glycol-water is heated from 2°C to 16°C. Meanwhile, the atmospheric air at 27°C also gets cooled to sub-saturation temperature.

According to an online publication [15] on the industry, commonly used heat-exchanger types are:

- Shell and plate heat exchangers (bundled/finned)
- Plate and fin type heat exchangers
- Air-cooled heat exchangers

3). Air-Cooled Heat Exchangers:-Air-cooled heat exchangers are those in which air is used to effect cooling of a large flow of liquid inside the tubes of heat exchanger. These comprise planar bundle of tubes assembled between headers at ends and plenum chamber with fan-bay. The design of ACHEs is as much art as it is science. Even so, nomograms are of great help in empirically determining sizing and final design by cutting-down pertinent calculations [16].

ACHEs can be used in fractional distillation or refineries of petroleum products where continuous flow [1] of hydrocarbons takes place.

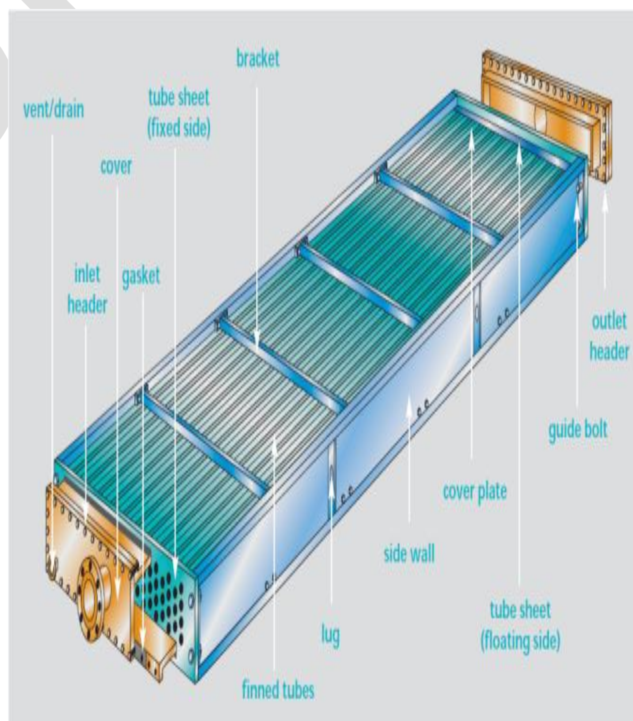

Figure 2. Air-cooled heat exchanger

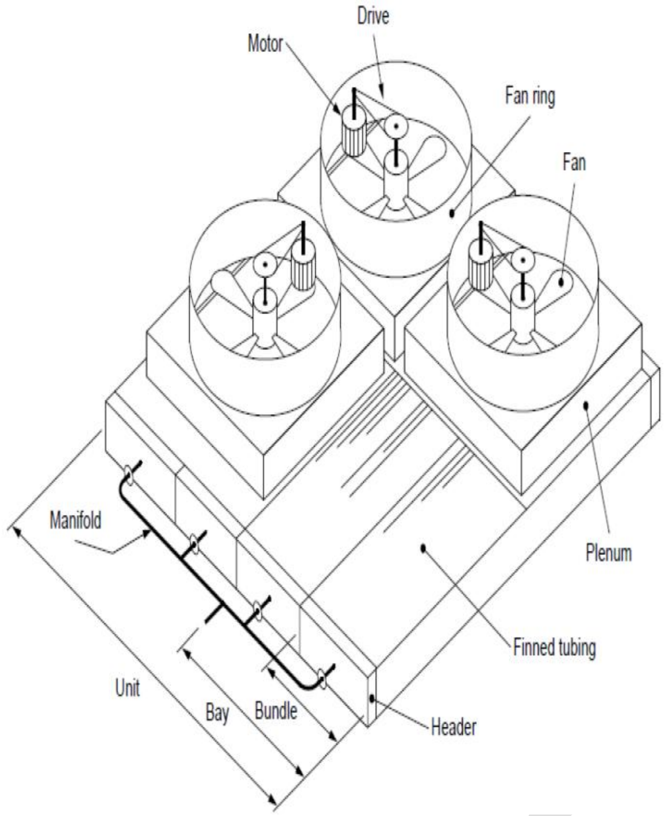

Figure 3. A typical isometric view of ACHE

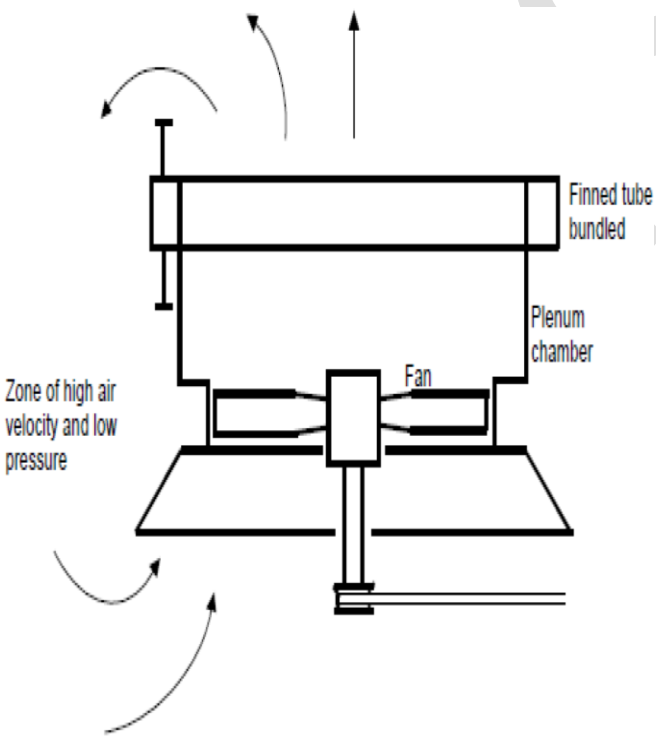

Figure 4. Air flow near forced-draught ACHE

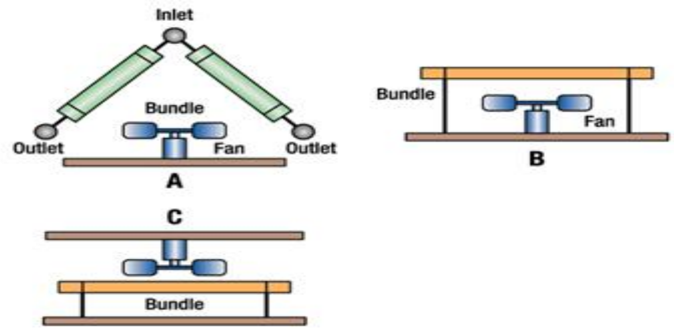

Figure 5. Types of ACHE's: (a) A-frame configuration with forced draft; (b) horizontal with forced draft and (c) horizontal with induced draft.

C. Header Box

A header-box (or simply, header) is welded box onto which the tubing is fixed connecting it to pipe (manifold). Although manufacturers have different nomenclature, common types are shown here.

Figure 6. Header-box of an air-cooled heat exchanger

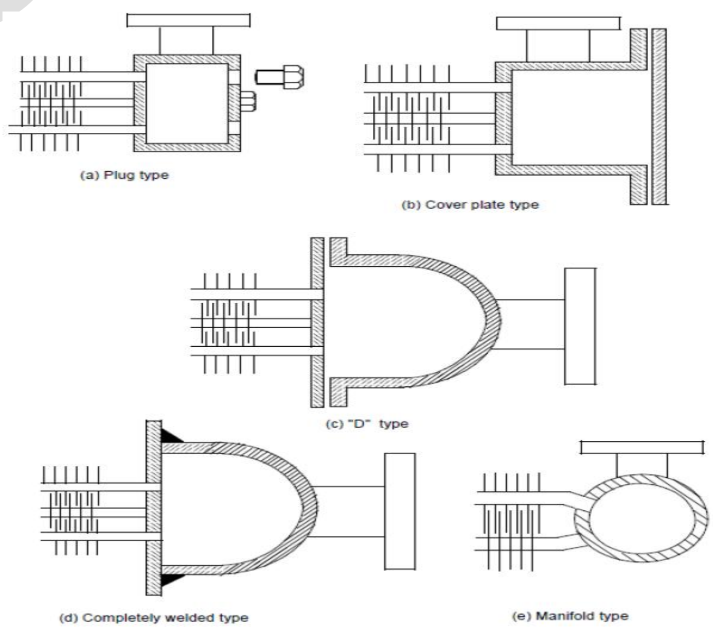

Figure 7. Types of header-boxes

Table 1. Application areas of header-boxes [18]

Application	Header Configuration			Finning type	
	Pipe & Bend	Plug Box	Cover Plate	Extruded / Embedded	L-Footed
Gas Re-injection	•			•	
Liquefied Natural Gas		•		•	
Gas Pipelines & Storage	•	•		•	•
Gas-to-liquids		•		•	
Refineries & Petrochemicals		•	•	•	•
Machinery Lube Oil Cooling		•	•	•	•

D. Defects in Heat Exchangers

ISO defines [17] an imperfection as a discontinuity or a deviation. Whereas defect is defined as an imperfection beyond permissible limits. Defects in heat exchangers are precarious given that safe operation is primary concern in an oil-refinery or a nuclear power plant. Therefore, even an insignificant manufacturing defect, though unlikely, can trigger a cascade of events. Manufacturers want to chalk out downright elimination.

Since air-cooled heat exchangers are manufactured fully by welding [18], defects pertaining to them arise mainly from improper welding techniques.

E. Standards

There are two main categories of standards that petrochemical industries and heat exchangers manufacturers adhere to:

1) Operational safety and

2) Manufacturing specifications

ASME [19], BIS, TEMA, NBBI [20], API, etc are associations that came into existence to curb accident-rates [19]. Regulatory authorities like IBR (Indian Boiler Regulation, 1950) [21] and OISD/OIDB [22] lay down safety standards in India.

F. Performance

Usually performance-evaluation of heat-exchangers is performed in academics [23] based on key-indicators:

- Hot and cold return/outlet temperatures
- Heat flow rate
- Overall Heat Transfer Coefficient
- Effectiveness calculations

G. Testing

Non-destructive testing (NDT) is defined [24] as the use of non-invasive techniques to determine the integrity of a material, component or structure or quantitatively measure some characteristic of an object.

NDT plays a crucial role in quality-assurance. Not only are these non-detrimental to products and processes, but also they are effective.

Table 2. Common NDT techniques [25]

Method	Abbreviation
Visual Testing/Inspection	VT/VI
Ultrasonic Testing	UT
Radiographic Testing	RT
Magnetic Particle Testing	MT
Leak Testing	LT
Dye Penetrant Testing	PT
Electromagnetic (Eddy-Current) Testing	ET

II. LITERATURE REVIEW

According to a paper [1], there is an urgent need for adequate extent of research-work associated with heat exchangers to be taken up. When it comes to air-cooled heat exchangers, the dearth of a comprehensive literature tends to undermine it.

A. Air-Cooled Heat Exchangers

A peculiarity observed from literature [26] [11] on ACHE's is that they are preferred to water / fluid-cooled devices owing to their inherent advantages:

- Maintenance-free operation (albeit cleaning is recommended)
- Water-scarcity not an issue
- Equipment-simplicity
- Cost-effectiveness
- Virtually zero fouling

A study [26] clearly shows a relation between fouling and subsequent failure in fluid-based heat exchangers. Therefore, air-cooled heat exchangers are crucial to any operation and thus to an organization.

B. Defects in Heat Exchangers

One task beforehand was to make out what the term 'soundness' implies. It is frequently used with other mechanical properties. It can be interpreted from literary works [27] [28] [29] to hint at mechanical perfection and signifies strength. A component with defects is not suitable to put into place as regards industrial safety. After manufacturing, Helium leak detection test can tell a sound heat exchanger from an unsound one.

A manufacturer, Kasera Heat Transfer Pvt. Ltd. [6] has indicated that manifolds are subjected to pressures of 200 bars. If the stress-distribution is uneven, distortion only adds to its woes. Refurbishing / re-tubing makes costs go up.

Distorted components can be hazardous as the gaps in resulting gasket or seal-linings may leak during operation. [6]

The strength of a welded joint has to be equal to or greater than the base metal. Defects tend to weaken the joint. Common defects in arc welding are classified as follows [30] [31]:

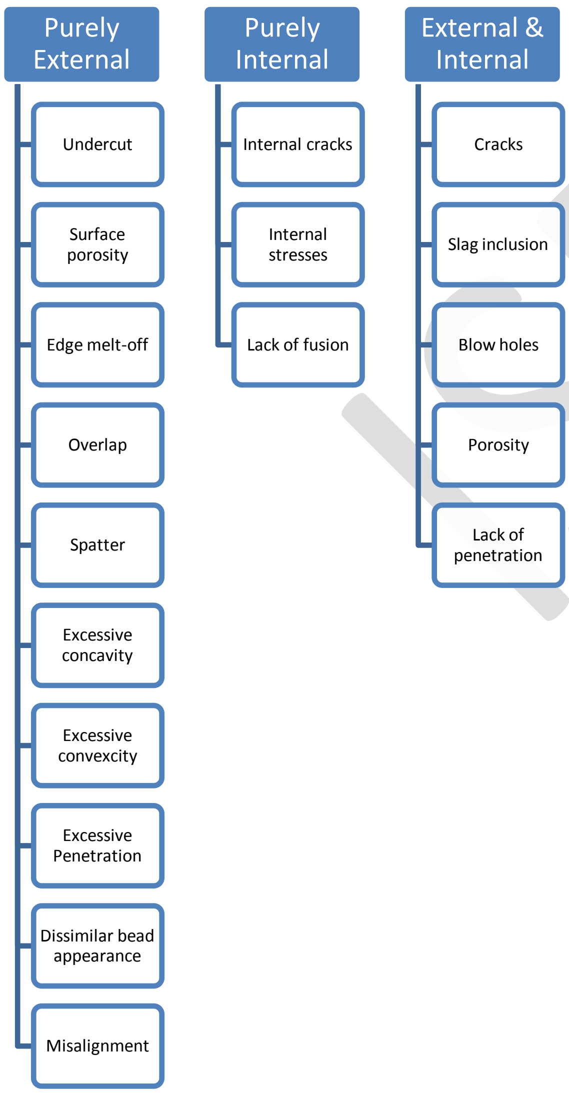

Figure 8. Types of welding defects

In contrast with DIN norms, distortion is also considered as a sub-type of shape-imperfection (as in ISO) [17] [32].

C. Distortion

Distortion is defined as a lasting deviation of original (from intended) shape and size of weldment after joining. An example of distorted component and modes of distortion are depicted.

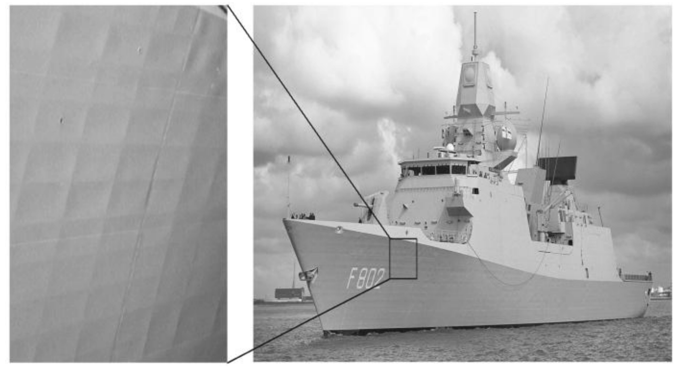

Figure 9. Buckling distortion on a ship hull [33]

1). Types of Distortion Patterns

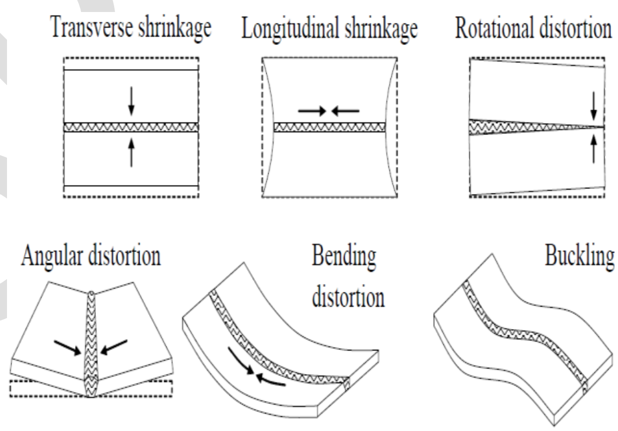

Figure 10. Various modes of distortion [33]

Common patterns in which distortion can occur along with shrinkage directions (shown with arrows) are shown above. Although welding distortion or warping can be attributed to differential heating or select strikingly distinct HAZ accompanying sharp temperature drop in surrounding cooler zones leading to shrinking and expanding, the main cause among several probable factors cannot be discerned without any substantial in-depth study [34].

2) Factors Responsible for Distortion

An attempt [35] was made to divide the controlling factors into design-related and process-related variables.

There can be a broad classification as shown in figure ahead.

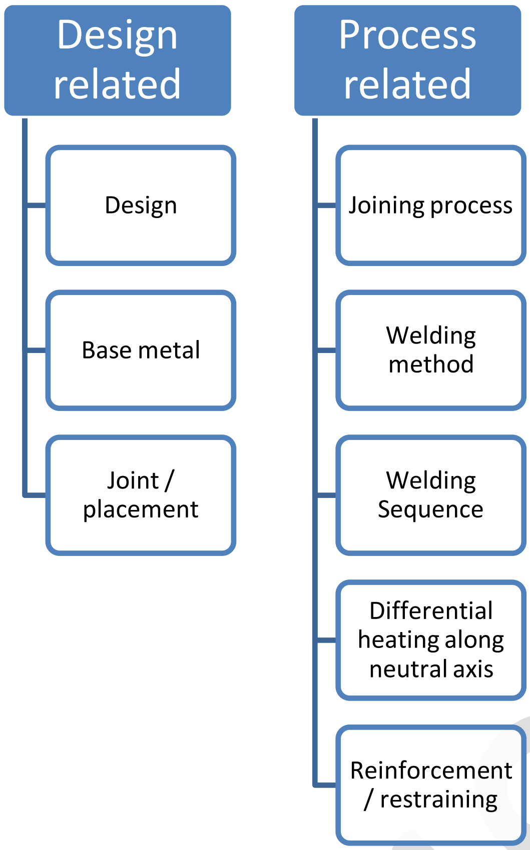

Figure 11. Factors causing distortion in welding

3). Testing of Distortion Patterns

Granted that welding distortion can be assessed by visual inspection, measurements are not uncommon on shop floors [36]. For comprehensive testing, rigorous monitoring, and analysis are carried out.

4). Prevention of Distortion

Extensive research in this area can be found in works done by Pilipenko [37], NIMI [30] and other experts [38] that stipulate remedies to control distortion by putting into practice the following means:

1. Methods of reducing effective shrinkage forces
    a. Avoiding over-welding / excessive reinforcement

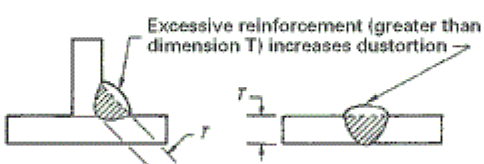

Figure 12. Overwelding

b. Use of proper edge-preparation and fit-up

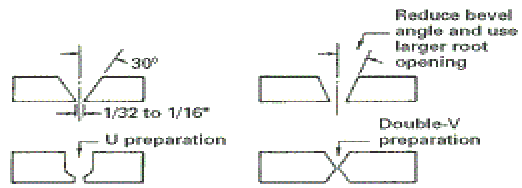

Figure 13. Edge-preparation and fit-up

c. Use of minimum passes

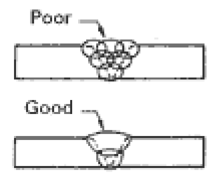

Figure 14. Few passes

d. Deep fillet weld (design alteration)

e. Use of intermittent welds

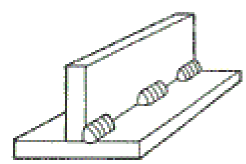

Figure 15. Intermittent welds

f. Back-step welding method

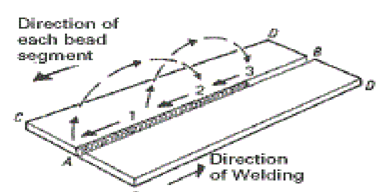

Figure 16. Back-step welding

g. Welding near centre (neutral-axis)

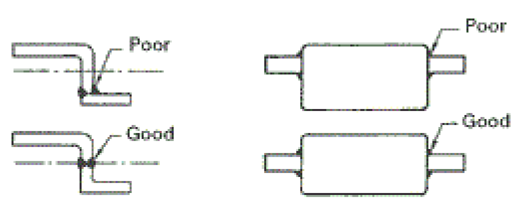

Figure 17. Welding near centre

h. Planned wandering method

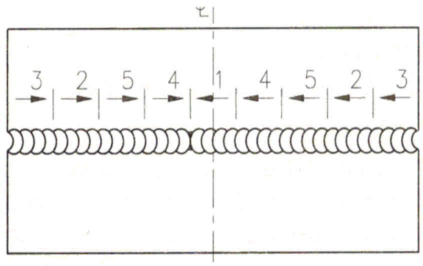

Figure 18. Planned wandering

i. Use of skip welding

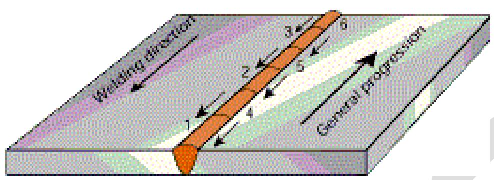

Figure 19. Skip welding

2. Methods of balancing of one shrinkage force with another shrinkage force
   a. Locating parts out of position

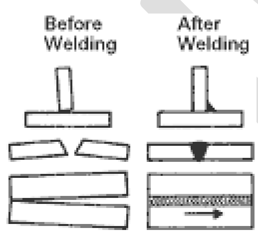

Figure 20. Pre-cambering / pre-setting

   b. Pre-bending

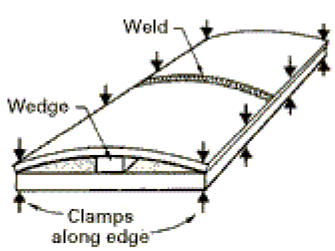

Figure 21. Pre-bending

   c. Shrinkage allowance

3. Methods of reducing compressive stresses
   a. Proper welding sequence

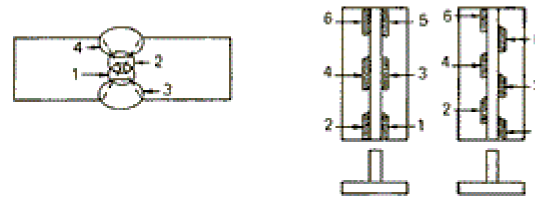

Figure 22. Welding sequence

   b. Peening
   c. Divergence allowance
   d. Pre-heating
   e. Jigs & fixtures

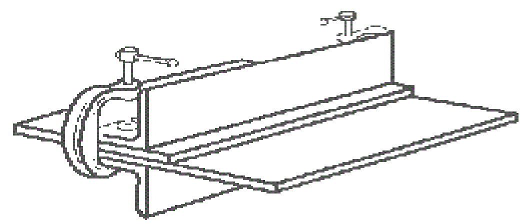

Figure 23. Jigs & fixtures

   f. Tack welding

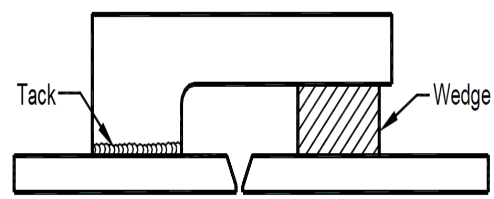

Figure 24. Tack welding

4. Methods of correcting distortion
   a. Mechanical methods
      i. Stress relief
      ii. Vibration stress relieving
   b. Heating methods
      i. Straightening by flame heating

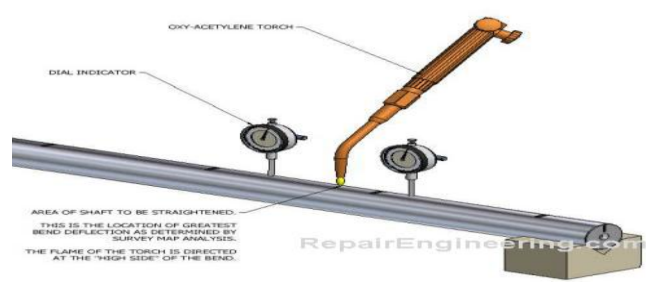

Figure 25. Flame heating straightening

i. Thermal treatments

- Pre-heating
- Post-heating

5). Effect of Material Composition

In practice, wherever industrial grades of steel are used, efforts are always to achieve high strength [37], low weight [39] and high corrosive resistance. Based on existing research, some effort has also been made to achieve what can be called distortion resistant metal [40], but that too relied heavily on shape features. As a matter of fact, it can be claimed without generalising that austenitic compositions are preferred to martensitic ones; exceptions to which, however, prevail [41].

6). Effect of Shape and Size

With the exception of presetting, pre-bending and other allowances, each weld-joint should be treated separately not only defined by its shape [42] [43], but also by its size [39] [44] [45]. Various algorithms have been developed for finite element analysis specifically as the case may be. These may differ from each other in some respect.

7). Effect of Thermal Expansion

Phase transformation plays a key role locally as far as distortion is concerned [38]. The outline of HAZ is represented here.

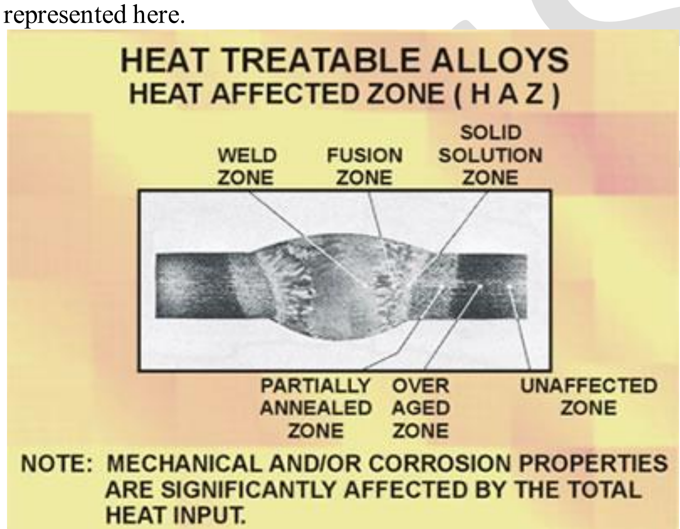

Figure 26. Heat affected Zone

Warping is inherently thermal expansion (and relative contraction) culminating from unrestrained (or selectively restrained) heating.

8). Effect of Pre-Heating

Preheating is a step in manufacturing sequences common to many processes (as in cutting) in which thermal actions tend to counteract with residual stresses and distortion. This is frequently deployed at shop floors.

Thermal stress relieving [38] is employed to prohibit the proliferation of distortion. TTT (Transient Thermal Tensioning) with stiffeners reduces buckling in thin structures [46].

As a rule of thumb [30], after pre-heating at 200°C, 33% reduction in warping is realized. For example, local preheating flame should be applied at point 'B' (as shown in next figure) to avoid cracking, if the fracture in the wheel at point 'A' has to be repaired.

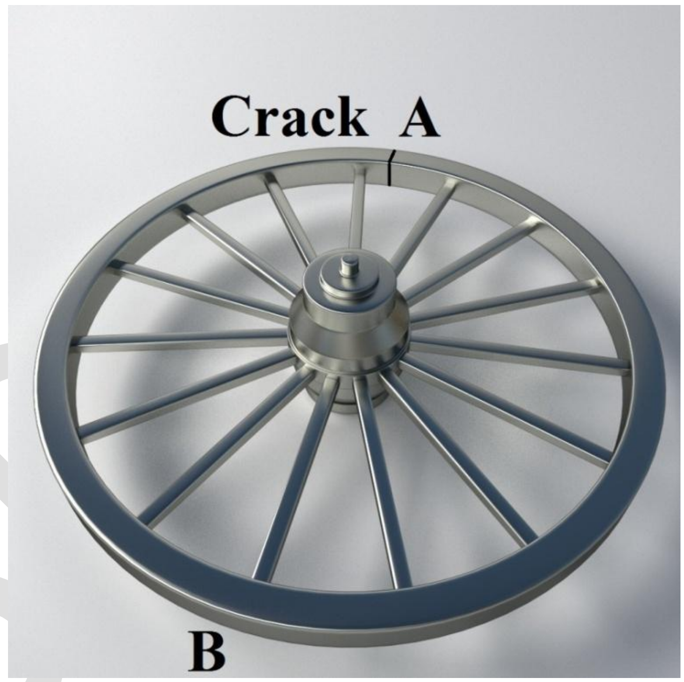

Figure 27. Technique of local preheating

9). Effect of Post-Heating

Even after apt welding methods have been ensured to prevent distortion, slow cooling at room temperature (as in annealing) or in furnace (as in normalising) can prove to be beneficial to [30]:

- relieve internal stresses
- make composition uniform
- refine grain-size
- improve machinability
- increase tensile strength and ductility
- eliminate undesirable brittleness
- prepare steel for hardening, quenching, etc.

Further, a very pragmatic approach of immediate (or even simultaneous) local cooling just after the weld-bead gets formed has been developed [33]. This is known as DC-LSND (dynamically controlled low stress no distortion) technique. Principally, the method is yet to be exploited to its full potential [47].

Apart from these, flame straightening is another popular method to dispense with bulges and unevenness arising from distortion.

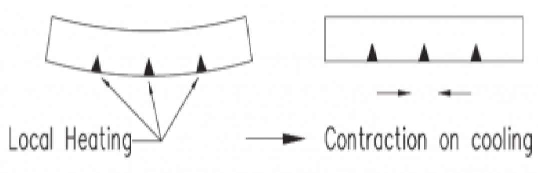

Figure 28. Flame straightening

What's more, high-frequency induction heating should be applied to mitigate the effects of longitudinal bending of built-up beams [48].

10). Correlation of Factors

Advance studies [36] [39] clearly reveal that distortion can only be controlled by a synergy of thermal, mechanical and material (phase) transformation processes. Since temperature and expansion are related, the factors of induced stresses (ensuing from applied strains) and the changes in material properties taking place as a result of phase transformation can be called to be interdependent.

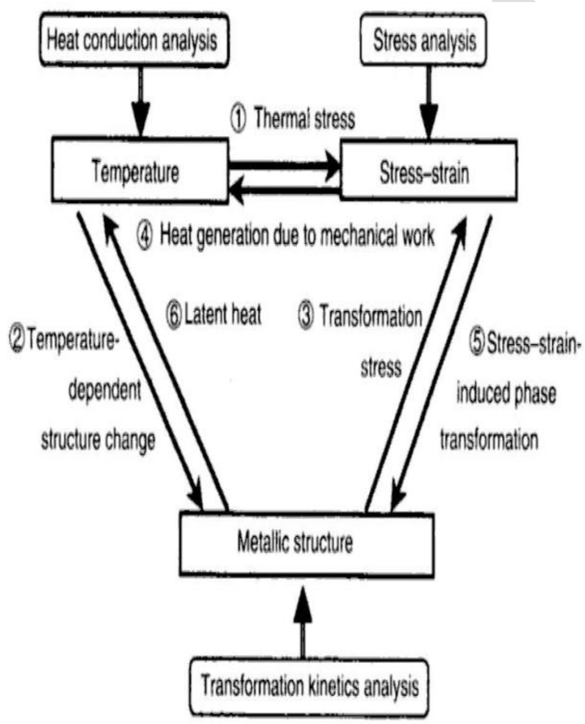

Figure 29. Metallo-thermo-mechanical coupling

11). Prediction and Forecasting of Distortion

While prediction of distortion is, in its own right, most unmanageable [44], a number of theories have been developed to anticipate distortion. Among these, few notable ones are discussed here:

- Laser (and hybrid) welding sources generate minimum distortion [37] [49] against maximum in flame sources (owing to concentrated heat). Their costs are high though.
- Finite element approach using local/global system is a common [50] and relevant analytical method (with fitting boundary conditions [44] or elastic FEA with initial gap [51]).
- Proper modelling and simulation [52] set forth that welding sequence and suitable preheating hinder martensite formation.
- For design and manufacturing optimizations (with distortion under consideration), welding and structural features can be decoupled [53] [54] and yet they prove to be an effective indicator (Thermo-elastic-plastic finite element analysis for welding simulation along with three-dimensional elastic and Eigen-value finite element analyses).
- Feng et al [36] discuss at large how FEA modelling strategies (keeping in mind heat-input, melting strain-relaxation and symmetry) can accurately predict distortion based on relationship between inherent shrinkage strains, weld residual strains, distortion and even extend it to initial deformation, adjacent welds, sequence and structural stiffness. Furthermore, heuristics approach involving AI is also suggested (notwithstanding the computational capacities associated with large structures). He, however, propounds deliberate contemplation for different thermal characteristics of a particular joint, its jigs (and fixtures) and the type of welding process.
- Neural network can be trained [55] for medium thickness plates, which provides forecasts in agreement with test results. Additionally, this helps to ensure structural accuracy as well.

12). Role and use of Fuzzy Logic

Given that artificial neural network has been a choice of experts according to a thorough survey (chiefly owing to its response by non-linear data from few numbers of experiments) [56], Fuzzy has emerged as another tool for dependable analysis [57] [58]. Fuzzy can be coupled with any of the prevalent techniques and can gratuitously be effective with results. Some of such existing methods are:

- Artificial neural network [59] [60]
- X-ray sensory noise [61]
- Particle swarm optimisation [62]
- Taguchi, ANOVA [63]
- Logic controller [64]

13). Possibility of Distortion due to inefficiency of welder

Welder competency is consistently [65] [66] evaluated before his or her employment. This includes his knowledge of distortion and its prevention and elimination. Huang et al [39] argue that post-weld treatments are non-value-added operations and call for a high degree of skill. In addition, automation (TTT) alone can be better alternative to efficient and skilled labour.

Since, for some reasons, efficient welders are decreasing in number [67], it becomes an imperative to ensure initial conditions of deflection (pre-stressing and pre-bending).

A standard [68] approach [69] to precisely predict residual stresses and improve efficiency was simulated taking into consideration the material (mechanical and thermal properties) parameters. This too endorsed proper sequences of runs. These and all other means (like edge preparation) [70] eventually have to be adopted by welders themselves at shop floor.

D. Standards

The codes given in ASME-BPVC Section-VIII (American Society of Mechanical Engineers, Boiler and Pressure Vessels Code, Section-VIII) and API-661 (American Petroleum Institute, Code-661) stipulate the manufacturing-guidelines, and after inspection, may provisionally issue stamps [71] (certificates) of authorization.

For example, American Petroleum Institute states,

"Threaded plug holes shall be provided opposite the ends of each tube for access. Holes shall be threaded full depth of the plug sheet or 2 inches, whichever is less. [72]*"*

"Ultrasonic examination is required for welds exceeding 2 1/2 inches (65 millimetres) in thickness. [73]*"*

The codes also cover shipment [74] and other guidelines (viz. installation) and must, therefore, be carefully scrutinized.

Additionally, companies develop their own 'design-by-rule' thumb-rules [75] accordingly. This initiative can also be investigated.

In India, BIS/IS has specified regulations [76] governing three classes of headers:

a) Removable bonnet headers

b) Removable cover plate headers

c) Plug headers

Manufacturers and oil & gas industries deal with more varieties like welded and high-pressure headers [12].

E. Performance

There can be more indicators than are actually studied in standard texts. Software modules [77] can visualize these. Moreover, various other factors can be taken into account. Cooling Technology Institute maintains [78] that mechanical components: fans and belts can affect (enhance or deteriorate) key-indicators.

F. Software

Apart from general software, a survey [79] among industry professionals shows that different companies use different software packages. Mostly, these cater to design-related needs. One such [80] is ASME's COMPRESS (published by Codeware).

For ACHE, GEI uses HTRI (ver. 6) which assists in thermal sizing [3], i.e. assessing the number of units according to power-requirements.

G. Testing

Non destructive testing can be useful in examination of distortion in ACHE's. GEI uses dye-penetration test, radiography (industrial-radiography) and remote visual inspection (borescope) in order to check the abnormalities in headers.

There can be errors during inspection as well. Findings [81] elicit that because of surface-finish, i.e., roughness, established modes of testing (as in Ultrasonic testing) may deviate from true picture. The possibility of false positive cannot be negated either.

Based on the tests [82] performed on air-cooled heat exchangers in past, we can also substantiate our methodology accordingly. During the Cold War, nuclear-powered aircraft [83] deploying air-cooled heat exchangers was supposed to be developed by US and the Soviet Union but the funding and the project were ultimately abandoned and decommissioned by the then President Kennedy. The report (now declassified by AEC) suggests that heat exchanger weldments had to be perfect. Moreover, the welders had to be perfect, which were nowhere near enough. Further, as always has been, advance technology was needed.

III. SUGGESTED METHODOLOGY

Once sufficient existing contemporary and relevant research has been surveyed and examined, what seems necessary is the course of action that is apt and systematic. This can only be embraced via following sequences:

- Ascertain the probable factors responsible for distortion
- Study and analyze the distortion patterns
- Finding and suggesting solutions in order to eliminate the distortion

IV. USE OF SOFTWARE

Wherever needed, appropriate software packages and modules would be deployed to carry on the research work.

These may be general software but can also be of specialized type on need basis.

V. EXPECTED OUTCOME

An efficacious research into this area is expected to deliver following outcomes:

1. Identification of factors responsible for distortion during fabrication of header-box of ACHE used in equipment of petrochemical process.
2. Study and analysis of distortion patterns based on identified factors / parameters.
3. Suggests ways / methods to minimise the distortion of a header-box of air-cooled heat exchanger during fabrication.

VI. CONCLUSION

As a result of detailed survey and technical investigation, the parameters that need to be considered to avoid distortion are the usual welding parameters (current, voltage, arc-length, speed, etc.). Future work should encompass thermal and process-related parameters as well.

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