EXPERT SYSTEM FOR DESIGN INTEGRATION - APPLICATION TO THE TOTAL DESIGN OF SHELL AND TUBE HEAT EXCHANGERS

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INTRODUCTION

The design process leading to the evolution of a working unit of heat transfer equipment is a prime candidate for AI implementation. The implementation certainly falls within the scope of a rule-based expert system. Expert systems are powerful computer systems designed for complex problem solving using a predefined knowledge base evolved from one or more experts in the area coupled with access to a multiplicity of analysis tools which may be used to provide decision making information [1-3]. A design process inherently involves the notion of a "search strategy". Available search strategies for AI expert systems are detailed in [2,4-6]. It is noted in [7] that the design process is usually thought of from an Individual Domain Viewpoint (IDVP); however for a complex system such as a shell and tube heat exchanger, the design process should be considered from a System Domain Viewpoint (SDVP). In the former case, in simple terms, an individual component of the system is optimized for the "best design" without regard for the rest of the system, while in the latter situation, each system component is designed in **parallel**, with the design strategy for each component **interacting** to optimize the design of the entire system, (perhaps at the extent of yielding less than optimum designs for the individual system components). **In terms of our emphasis here, most current (non-AI) heat exchanger design is carried out using a noninteracting IDVP; we suggest that an integrated SDVP, coupled with an expert system serving as an overall shell for parallel design processes, can evolve the best performing and most reliable unit.**

As is shown in detail in a subsequent section, overall design of a particular heat exchanger encompasses a wide variety of problem areas involving both quantitative and qualitative information and results. We will focus on a detailed examination of these problem areas to identify particular design methodology attendant to each. We summarize the entire design process for heat transfer equipment under the following modules:

a. Architectural
b. Thermal-Hydraulic
c. Mechanical-Metallurgical
d. Operation and Maintenance

As we have noted, current design philosophy for this equipment is **serial** with little interaction between particular engineering groups. Indeed, it is often the case that items "a" and "d" are within the province of the user's engineering group, while items "c" and "d" fall under the purview of the equipment supplier. Generally, there is little interaction between these groups and no attempt at coordination of the design process between items. We hypothesize that it may be fruitful to study the potential for such interaction by treating the entire design process for this major industrial component as a set of **parallel** processes involving a total system; the design processes are aided by existence of rule based computer aided expert which provides interaction and communication between problem areas and enables the appropriate information to be acquired, and the correct questions to be asked at the right time by the right engineering groups. Fig. 1 shows a possible schematic for such an expert system.

EXPERT SYSTEM FOR HEAT EXCHANGERS - NEEDS AND REQUIREMENTS

Heat exchangers are at the heart of many industrial operations. A great bulk of capital equipment cost in a power plant, for example, relates to the heat exchange equipment and appurtenances. The pivotal place of heat exchanger equipment in industry is evident from the large body of codes and standards developed by numerous organizations, and the growing volume of research literature on the subject. References [8-17] illustrate Codes and Standards most frequently used in the U.S. Most other industrial nations have many of their own indigenous standards, usually supplemented by some of the U. S. documents.

The sheer quantity of information in the heat exchanger technology literature makes the quality of the design highly dependent on the know-how, interaction, and experience of the entire design team. Unfortunately, instances of heat exchanger piping being designed by Mechanical Engineering groups, being relocated by Civil Engineering groups, and being relocated again by the erector (due to piping interference) are far too common. Reliability and maintainability of the heat exchanger is the main victim in this "shell game." It would be safe to say that not a single power plant built in the U.S. in recent memory has escaped this kind of reiterative design process in one form or another with a direct impact on ultimate performance and serviceability of the heat exchanger.

In contrast to non-intricate items such as piping or one of a kind items such as the boiler, heat exchangers are both sophisticated in construction and ubiquitous in presence. The wide array of architectural, thermal-hydraulic, and mechanical considerations, spread over dozens of governing and reference documents, makes the evolution of a flawless design by a large group of engineers an improbable scenario. The industry experience to date bears out what might be speculated. The rather low power "availability factor" of power plants (less than 60% nationwide) can be attributed in large measure to the pell-mell design process of heat exchangers. **An expert system which coalesces the design, operating, and maintenance considerations will undoubtedly have a major impact on state-of-the-art plant design technology.** We present a brief synopsis of the major considerations that should be included in any such expert system under categories: (i) architectural; (ii) thermal-hydraulic; (iii) mechanical/metallurgical; (iv) operational; and (v) maintenance.

(i) Architectural: Some of the architecture considerations in heat exchanger design are:

(a) How to orient the unit - horizontal, vertical, or inclined?
(b) Should fluid inlet and outlet connections be located near the floor, near the ceiling, etc?
(c) How will the unit be situated in the plant?
(d) What utilities are needed? Drains in the floor, etc.?
(e) What size hatches and openings are available to transport the unit into place?
(f) Do stairs, posts, etc. interfere with bundle or shell removal?
(g) What size cranes, dollies, rail tracks, etc. are needed to install the heat exchanger?

(h) What facilities for in-service inspection, such as cat walks, ladders, etc. are needed?

(i) Is there a provision for thermal insulation?

(j) What is the required net suction head on the pump and what head is available?

(k) What considerations govern whether to use a steel frame or to use reinforced concrete flooring?

(l) What are the seismic, wind, and other loads on the equipment floor and how will they impact the unit?

(ii) Thermal hydraulic considerations: Heat transfer is, of course, the raison d'etre for the heat exchanger; therefore, thermal considerations occupy a central place in the unit design process. Types of heat transfer processes involved, however, vary greatly, as does the importance and relative significance of various considerations. A representative list of design questions that must be considered is given below to clarify this point.

(a) Type of heat transfer, viz., boiling, condensing or single phase heat transfer. Is the process a combination of phase change in portions of the exchanger, and no phase change in other portions?

(b) Since the heat exchanger has two pressure chambers, which chamber should receive the coolant, and which one should receive the fluid being cooled?

(c) What kind of shell pass and tube pass arrangements will produce maximum heat flux?

(d) Are the nozzle orientations consistent with architectural layout?

(e) What kind of internal flow areas are required to prevent erosion?

(f) How will the exchanger respond to changing plant load conditions?

(g) Are there provisions for perils such as localized flashing, etc.?

(h) Is the design immune from flow induced vibration?

(i) Does the design minimize the fouling of tube surfaces?

(j) Does the design provide for efficient expulsion of non-condensibles where the unit is such that even small accumulations may grossly derate the performance? (A prime example in this category is "Surface Condensers.)

(k) In units involving boiling, how much droplet entrainment in the vapor is acceptable? How is the target amount of de-entrainment achieved?

(l) How much pressure loss is acceptable in tubeside and shellside chambers? Is the sum of the pumping cost and the initial equipment cost minimized?

(m) How does a variation in temperature rise of the fluid affect the overall plant performance? For example, a 1^{o}F increase in the feedwater outlet temperature in a heater may be worth $50,000 of "present worth" to the plant owner. The cost of enhancing the heater to accomplish this may be less than $10,000.

(n) What thermal/hydraulic restrictions on routing of the inlet and outlet streams exist?

The above list describes only a representative sample of the multitude of thermal/hydraulic considerations that ought to be considered. The above sampling indicates that a "total" design process must involve an interplay of "mathematical analysis", and empirical guidelines. For example, whereas the pressure loss in a heat exchanger stream can be mathematically calculated, prediction of erosion rate is largely predicated on empirical guidelines and past experience.

(iii) Mechanical design and materials selection: The selection of proper materials for wetted and non wetted parts, pressure and non pressure parts, and equipment support is an extremely important design step. The American Society for Testing and Materials (ASTM) gives data on a large number of ferrous and nonferrous materials. Many of these materials have been adopted by the ASME Boiler and Pressure Vessel Code. However, ASTM data is restricted to the physical properties, such as Young's modulus, yield strength, minimum tensile strength, elongation, coefficient of expansion; thermal diffusivity, etc. Information on other important phenomena such as galvanic corrosion, stress corrosion, pitting in a particular fluid environment must be gleaned from disparate sources, and is often difficult to find.

The required type of heat treatment to be given to a particular material in a particular application is yet another subject with a large body of data diffused throughout the literature. Yet, its importance on the equipment longevity cannot be overemphasized. For example, a solution annealed austenitic stainless steel tube may last years in service, while its counterpart in the so-called "sensitized" state can fail in a halide environment within days!! The interaction of corrosion inhibitors, algae suppressant and the like on heat exchanger material preparation are effects that behoove due consideration, but often receive scant attention due to lack of readily accessible information.

The mechanical design portion of the overall exchanger design process offers the richest variety of options, and choices which strongly shape the reliability of the hardware. It is also the segment of work most replete with codes, standards and myriad "good practices." The most important document is the ASME Boiler and Pressure Vessel Code, which lays down mandatory rules for computing thicknesses of pressure parts, acceptable weld sizes, and other details. The thicknesses of heat exchanger shell, head, flat cover, raised face flanges, etc. are governed by Code rules. However, many shapes of construction, particularly the tubesheet, pass partition plates, expansion joints, shell longitudinal baffle, are not covered in detail by the Code. Such voids in the Code are partially covered by industry standards. The most prominent among them is the "Standards for Tubular Exchanger Manufacturers Association" (the TEMA standards"). However, even though TEMA covers most commercial exchanger configurations, many important parts are not treated, or are only empirically specified. For example, no design guides exist for flanged and flued expansion joints and for reverse disk heads. Rules for pass partition plates, longitudinal baffle and other internals are entirely empirical. Despite lack of coverage in standards, there has been a great deal of analytical and numerical work to provide rational bases to design component parts for which rules either do not exist, or are inadequate in all but common conditions of service. Much of the technology available outside the standard design codes and standards is documented in reference [18]. The quantity of information required to arrive at the most optimal design is scattered over several documents, and even within a document is not arranged to synchronize with the steps of the design process. In view of our proposed expert system concept, it is worthwhile to summarize a typical sequence of decisions that are required to be made at the mechanical design stage of a heat exchanger design.

(a) What kind of connections (welded, flanged or packed) should be provided at the front channel, tubesheet and rear head locations?
(b) What style of flanged joint should be used; e.g. full face, ring type? (the choice has important effect on joint sealability).
(c) What kind of gasket material to use? (over 100 choices exist)
(d) What kind of closure heat should be considered? (ellipsoidal, torispherical, etc.).
(e) What load combinations will govern the pressure part design? (Typical loads are shellside pressure, tubeside pressure, differential thermal expansion, deadweight, seismic closing and mechanically transmitted vibration.
(f) Type and style of manways (openings).
(g) Type of nozzle connections, i.e., self-reinforcing forging stock vs. pipe schedule.
(h) Type of tubesheet stays, if any to be used.
(i) Details of vent and drain designs.
(j) Minimum bend radii for U-bends.
(k) Should shell course thicknesses be equal or unequal?
(l) Is there any internal differential expansion relief required? If so, what is the best type and style of the expansion joint?
(m) Type and style of heat exchanger supports - qualification under loading.
(n) Evaluate the ability of the exchanger to withstand operational transients, start up.

Each of the above listed design decisions and evaluation steps requires a proper adjudication among competing considerations; many of these considerations require and are amenable to mathematical analysis, while others are derived from prior experience or laboratory experimental data.

(iv) Operational Considerations: Many ostensibly astute design from the equipment designers' vantage point, may turn out to operator's nightmare. A highly efficient heat exchanger may perform miracles in transferring heat in a compact size. Yet, it may be an inherently unstable and unreliable piece of hardware; that is, it may be subject to rapid fouling or tube failure if operating conditions pulsate. It may be too sensitive to system input data making it difficult for the plant operators to control its performance in the face of changing output requirements. In certain cases, it may be a high performing piece of hardware itself, but yet pass on to the downstream equipment its deficiencies and lead to problems in other equipment. The possible conditions of undesirable plant performance are legion. Proper exchanger design ought to evaluate the operational characteristics of the heat exchanger as an organic part of its system, and provide appropriate feedback at the design stage so as to minimize propagation of problems to other system components.

(v) Maintenance: Maintainability of the heat exchanger is perhaps the farthest removed from the equipment designer's attention. Yet, its importance cannot be minimized. To design for maintenance requires a proper definition of maintenance for the particular hardware. This should be well understood at the design stage, for example, design for maintainability requires consideration of how many tubes, if any, can be plugged before the unit will be retired; will the tube bundle be replaced saving the shell and/or the channel barrel, or should the entire unit be replaced? Having circumscribed the intended maintenance and rehabilitation goals, the necessary questions for evolving a maintainable heat exchanger can be raised and answered. Some typical maintenance related items that must be considered by an "expert" are:

(a) Tube pull space required for retubing.
(b) Davits, hinges, eyebolts, etc. for removing manway covers, channel covers, heads, etc.
(c) Dowel pins for aligning mating flanges.
(d) Ease of gasket replacement.
(e) Ability to maintain one pressure chamber pressurized while the other is opened up for maintenance.
(f) Ability to monitor tube leakage, weld joint failure, etc.
(g) Ability to plug tubes, replace worn-out studs, etc.
(h) The facility to perform in situ welding and machining operations.
(i) Interchangeability of parts, e.g. gaskets, tubes, studs, nuts, etc.

The type of maintenance considerations certainly depend on the nature of the service of the equipment. For example, fouling of tubes is a non-concern in feedwater heaters which have highly purified fluid medium in them. On the other hand, fouling inside tubes of surface condensers is a major concern, placing a premium on designs that permit quick access for tube cleaning. Often condensers are made in two halves (divided waterbox construction) such that tube cleaning (and other maintenance, if necessary) can be carried out in one half, while the other half can be kept in service. There are numerous other instances of maintenance consideration playing a crucial role in shaping the heat exchanger design.

SUMMARY

A scenario has been proposed to create an expert system to examine parallel design of a major industrial component. An outline of the needs and requirements of such an expert system has been suggested. While the complete system may be too large to develop in one project, it is certainly feasible to focus on a small part of the problem area to gain experience in the application of expert system development in this area.