

Technical Note

Heat Transfer Equipment for Space Shuttle Orbiter, Its Main Engine (Aerojet Rocketdyne RS 25), Thermal (Passive and Active), Environmental Control and Life Support System

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Abstract: Space shuttle has been a hall mark of American space program since its inception. Despite its temporary shutdown few years ago, with the recent interest in space exploration which includes revitalizing human outpost in microgravity and transportation required to build it, realize other experiments (e.g. in space telescopes, in space manufacturing) and interplanetary voyages, it has regained attention. Its superior design, manufacturing, materials, performance, durability, and efficiency place it among the best, in fact, the only effort by mankind to build a reusable craft horizontally, launch vertically like a rocket and fly back like a plane. Various requirements emerge during its design (thermal, fluid, acoustics, vibration and structural) and design of its main engine (Aerojet Rocketdyne RS 25) which requires considerable attention, heat transfer being most important. This facilitated and necessitated use of various types of heat exchangers such as single coil, heat pipe, built in internal heat exchanger (IHEX), external heat exchanger (EHEX), condensing heat exchanger (CHEX), Interface heat exchangers (InHEX), regenerative heat exchanger (RHEX) and compact heat exchangers (CoHEX), change, manipulate and optimize their configurations in piping and instrumentation diagrams (PIDs). In this short narrative, an effort has been made to summarize them, and their developments over time with a focus on the application, design, manufacturing, materials, and performance (in service and final operation).

Keywords: heat transfer; thermodynamics; evaporation; condensation; regeneration

1. Introduction

Space shuttle orbiter has been an active and challenging space craft since its inception even during design phase [1, 2]. It has various moving and stationary parts and components which systematically and synergistically operate to realize its flying. One of them is its main engine. It consists of fuel chambers (Liquid O₂ and Liquid H₂ (LOX)) which are connected to main combustion chamber by various tubing and valves intermittent of which, as per requirement (thermal, heat transfer, energy efficiency, fluid and thermofluidic), various auxiliary heat transfer equipment (e.g. low and high pressure turbo pumps (fuel and oxidizer), injectors and pre burners) are installed to best make use of available resources (fuel, material, energy and manpower) (Figure 1 a). Each is connected in tandem (forming closed loop) and hosts controller as well. Design of engine depends on fuel (type, amount, amount consumed / second, density, viscosity, heating value, flash point, acid value, pour point, cetane number and their temperature dependence (transient processes)) which in turn depends on intended orbit, orbital insertion parameters, planetary drag, atmospheric drag (coefficients) and their relationship with point of launch on earth.

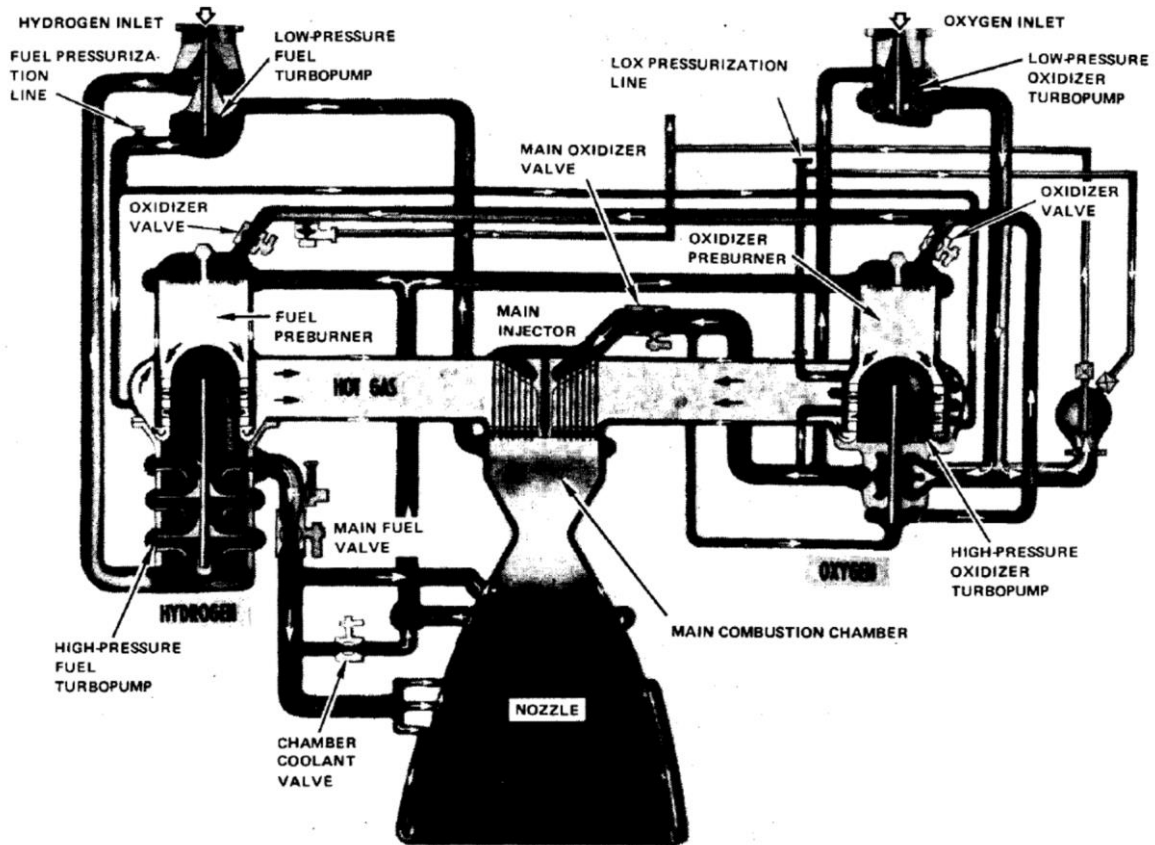


Figure 1. (a) Propellant flow schematic – space shuttle main engine (RS – 25) assembly [3].

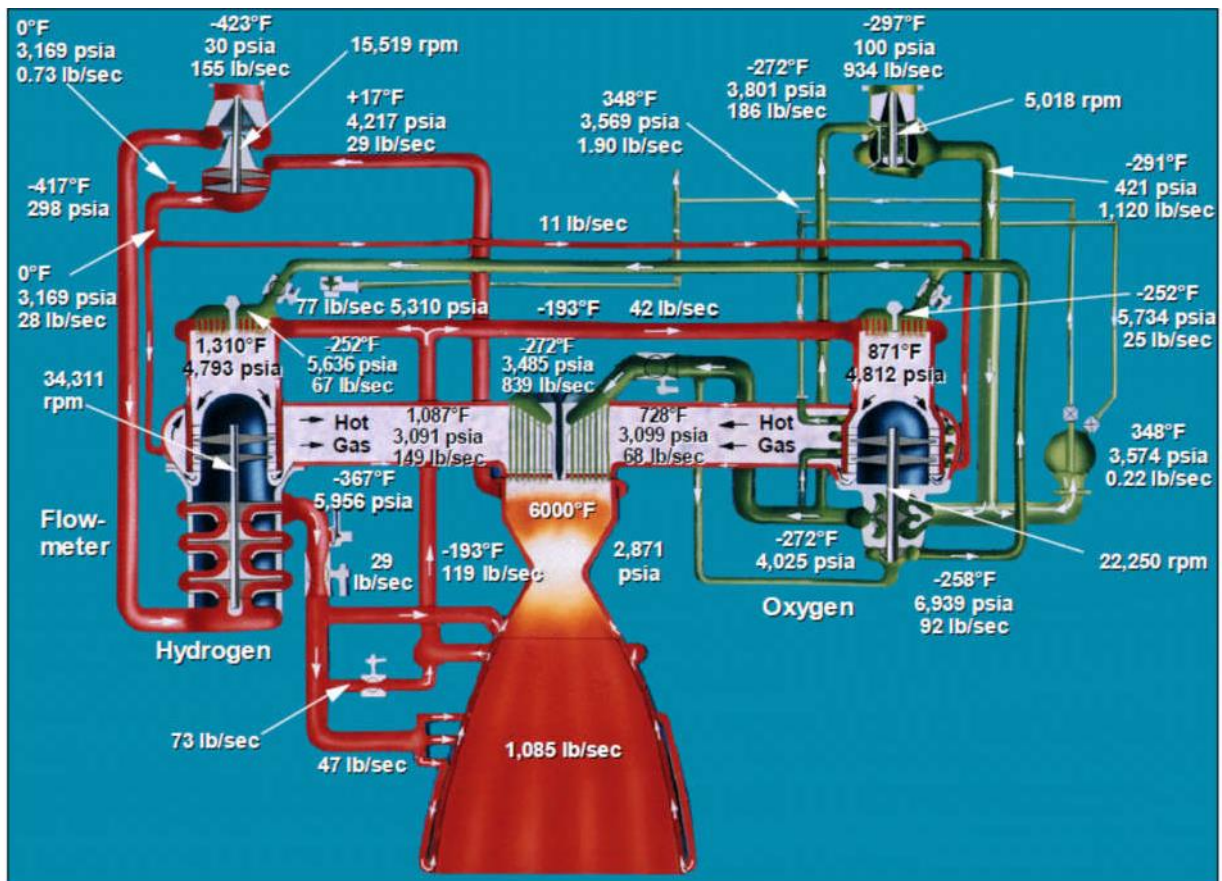


Figure 1. (b) Propellant flow schematic – space shuttle main engine (pumps, valves, and tubing).

It also has an optimized exit in the form of nozzle (bell shape) which again has various sub systems in it (e.g. cryogenics, regenerative heat exchanger, tubing and reinforcements) (Fig – 2).

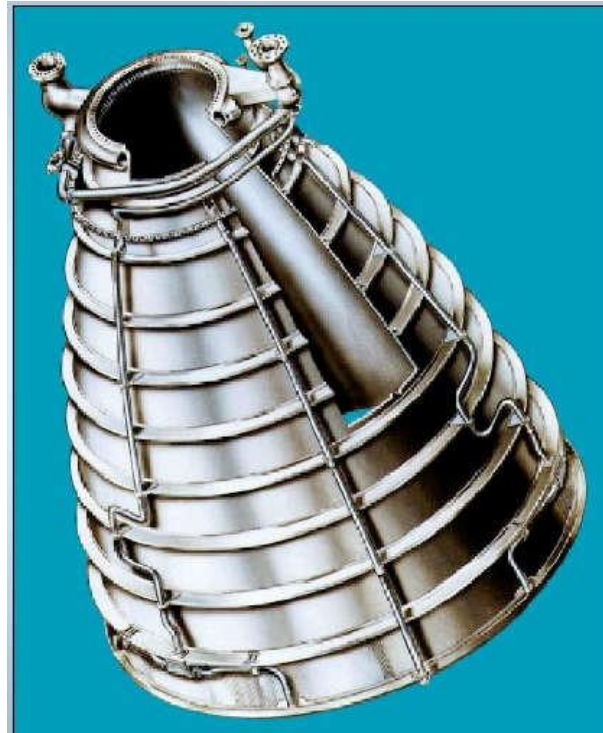
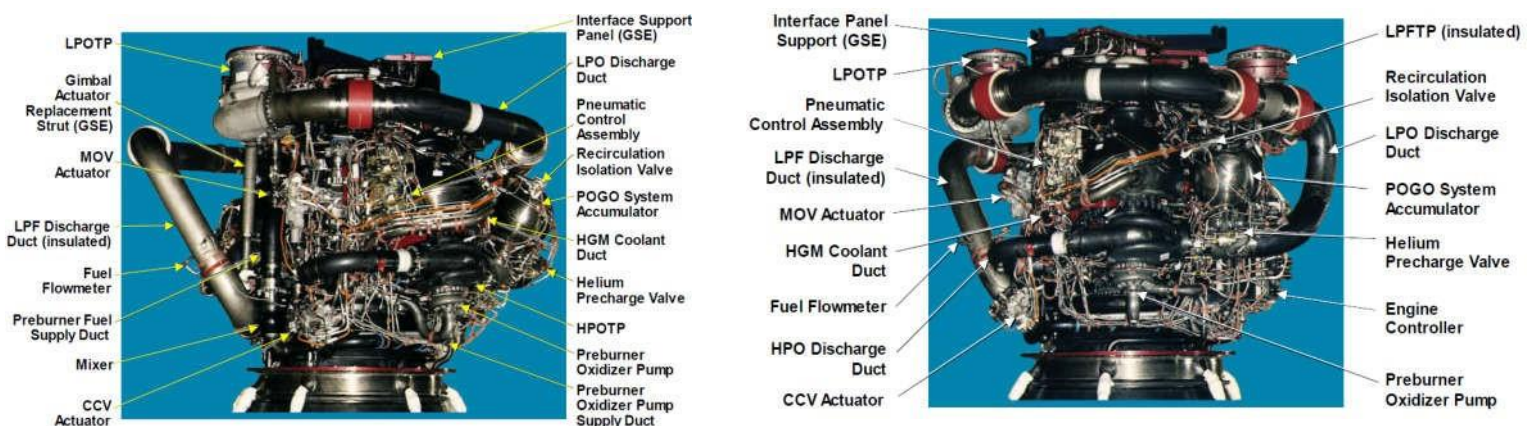


Figure 2. Bell shape nozzle.

This is connected to combustion chamber and main engine pressure assembly by a gimbal joint (explained elsewhere). There are three main engines on a space shuttle orbiter placed with their center at each vertex of an equilateral triangle. Despite two fatal accidents to space craft shuttles (STS 51L and 107), its engines have 100% safety record. It has a limitation of having high running cost, but this is augmented in various stages of its evolution by various adjustments and modifications (outlined here).



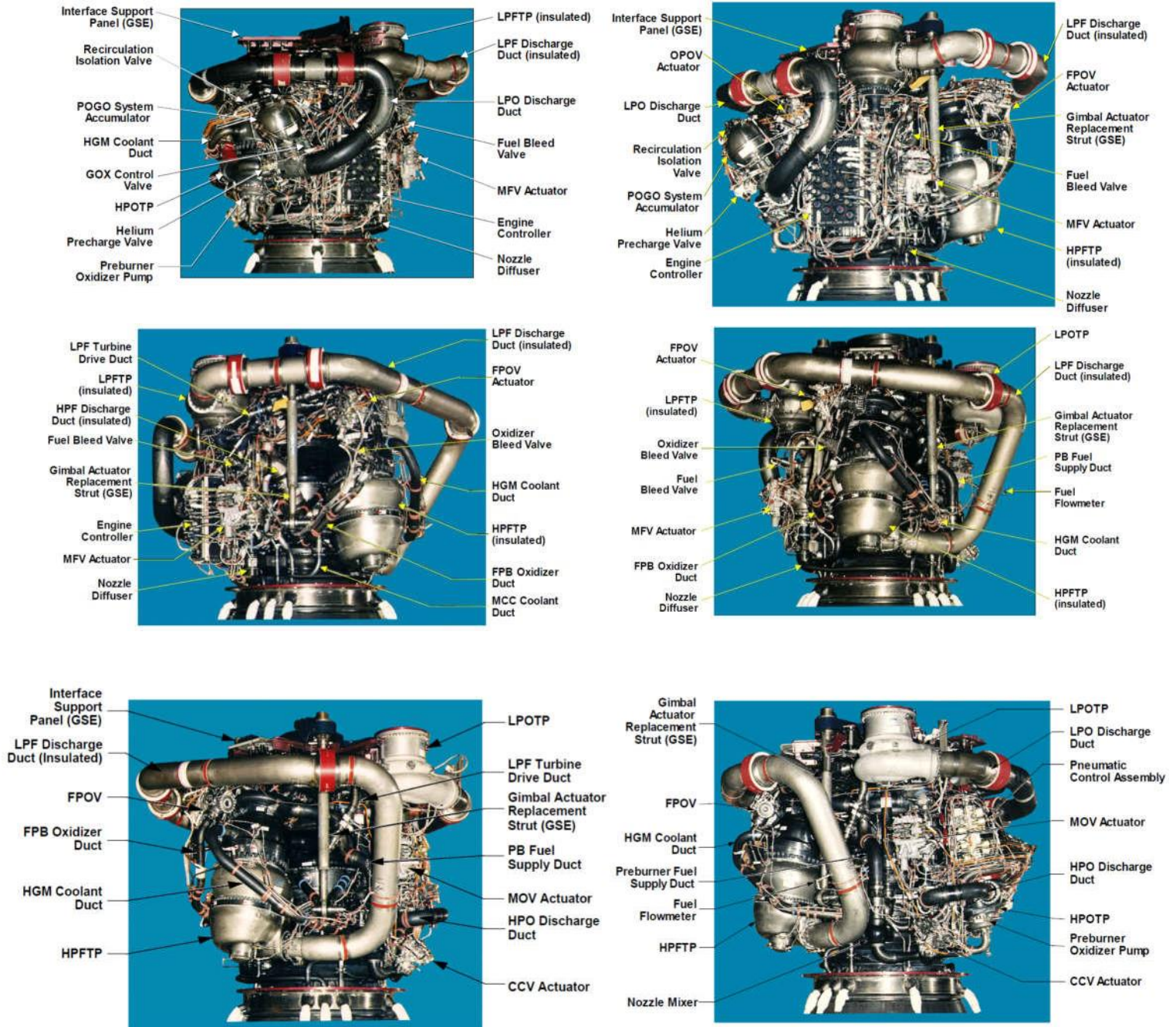


Figure 3. Typical space shuttle main engine (SSME) pressure head, view 1 – 8.

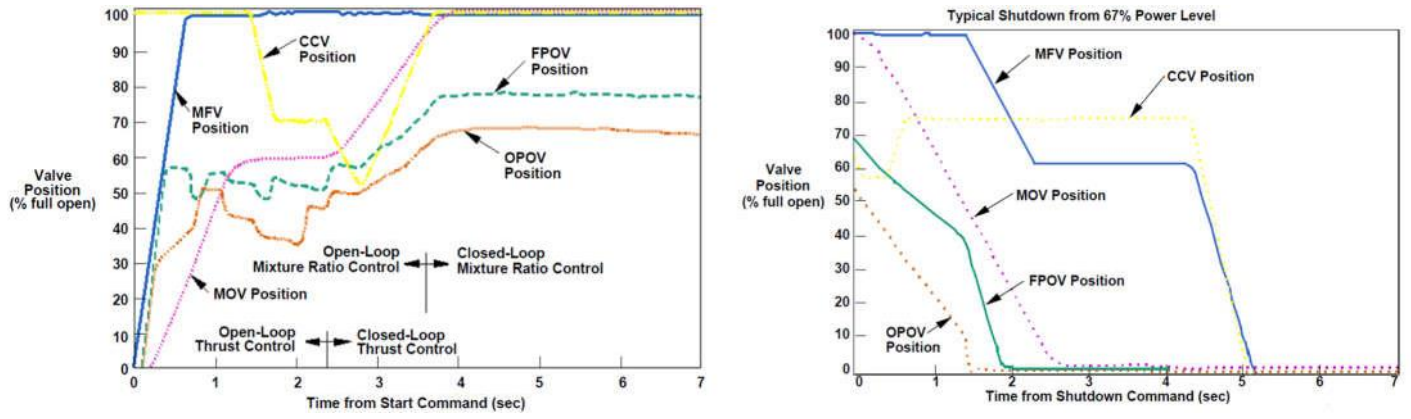


Figure 4. (a) SSME start sequence, (b) shutdown sequence [3, 4].

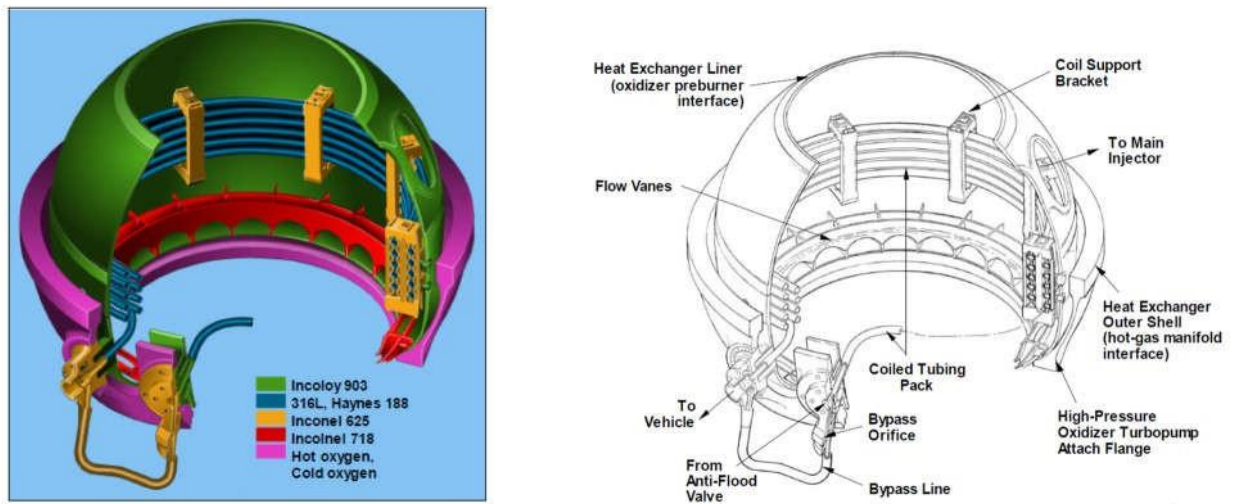


Figure 5. (a) SSME heat transfer, (b) Exploded view [3-10].

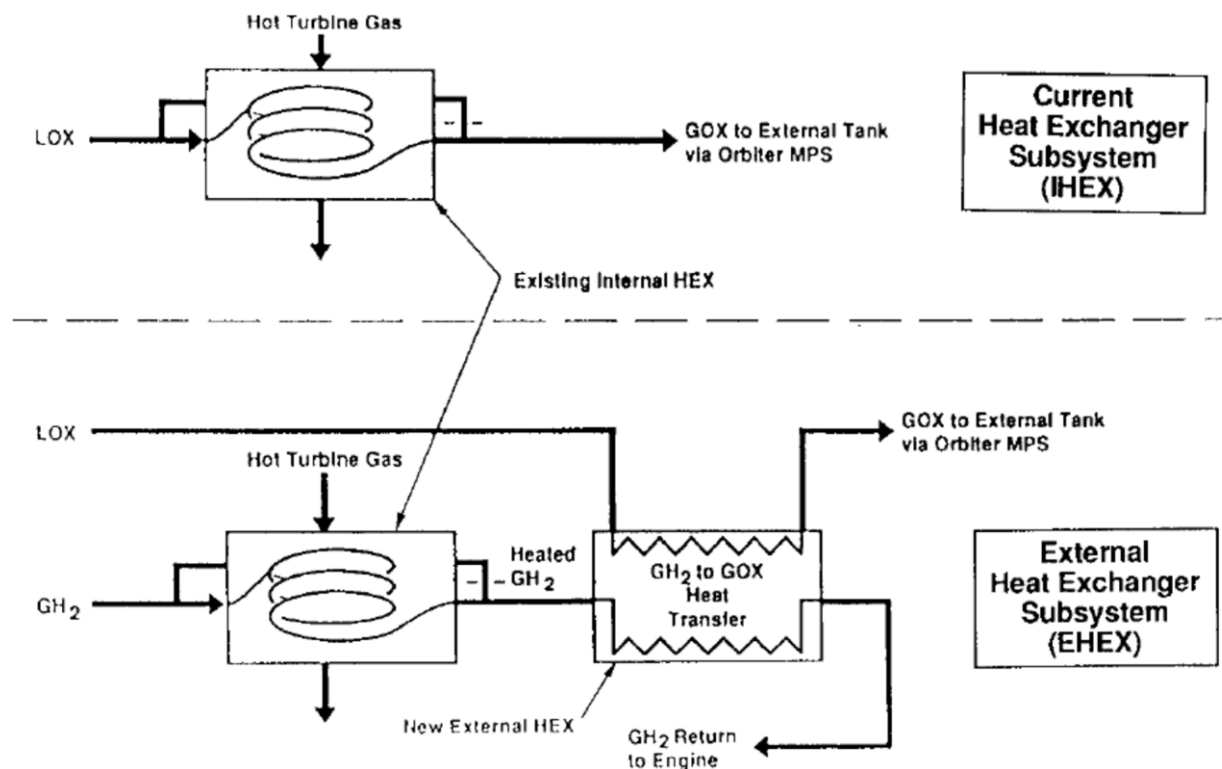


Figure 6. Conceptual comparison of IHEx and EHEx [9].

2. Role of SSME start phase and sequence

SSME start phase and sequence has an important influence on the heat exchanger performance. Position and place of heat exchanger in fuel, pressure and ignition loop is very important and bears a significance towards its in-loop operation and performance. Start phase and sequence of starting an engine has a significant effect on performance, efficiency, and its operational output (amount of heat transferred). Heat exchanger controls the flow of gases, regulate them, their temperature, pressure and hence energy being transferred. As shown above (Fig 6), conceptual internal and external heat exchanger bears a significant effect on engine performance. Below figures (Fig 7 – 9) show different modes in which SSME may be powered and its actual valve opening procedure sequence (% age full open Vs time from start plot). Though scientific in nature, this plot is an easy guide for a layman to understand when and how to operate, and how much to open a valve to achieve a certain thrust from an engine. Still, an unfortunate accident STS 107 took place due to carelessness and ignoring the safety and operation instructions by Kal- pna Chawla which resulted in casualties of all 7 crew members as well as orbiter itself. This also resulted in shutdown of program which is revived now.

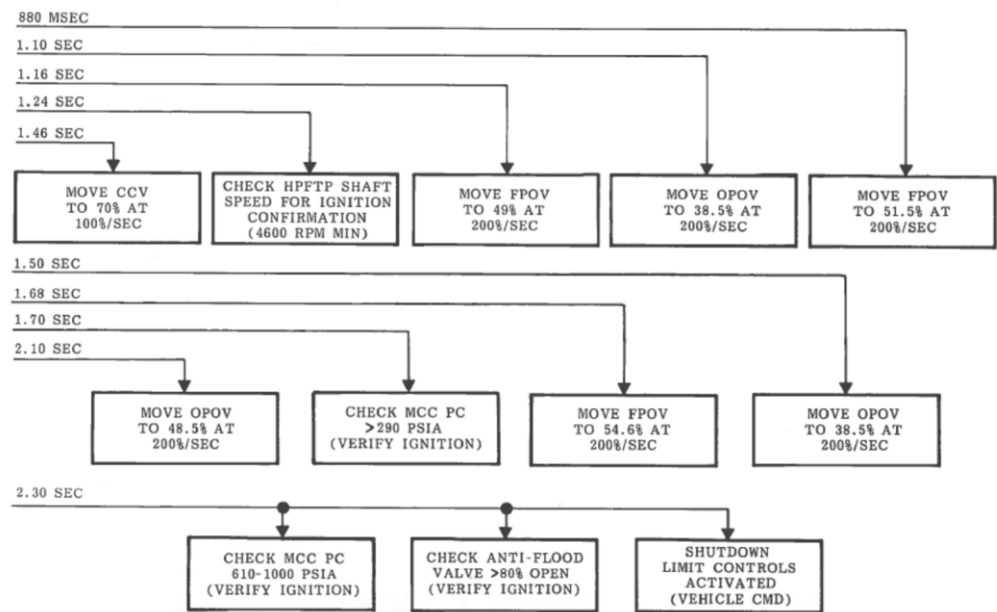


Figure 7. SSME start phase (start initiation mode – continued, nominal duration = 2.4 sec).

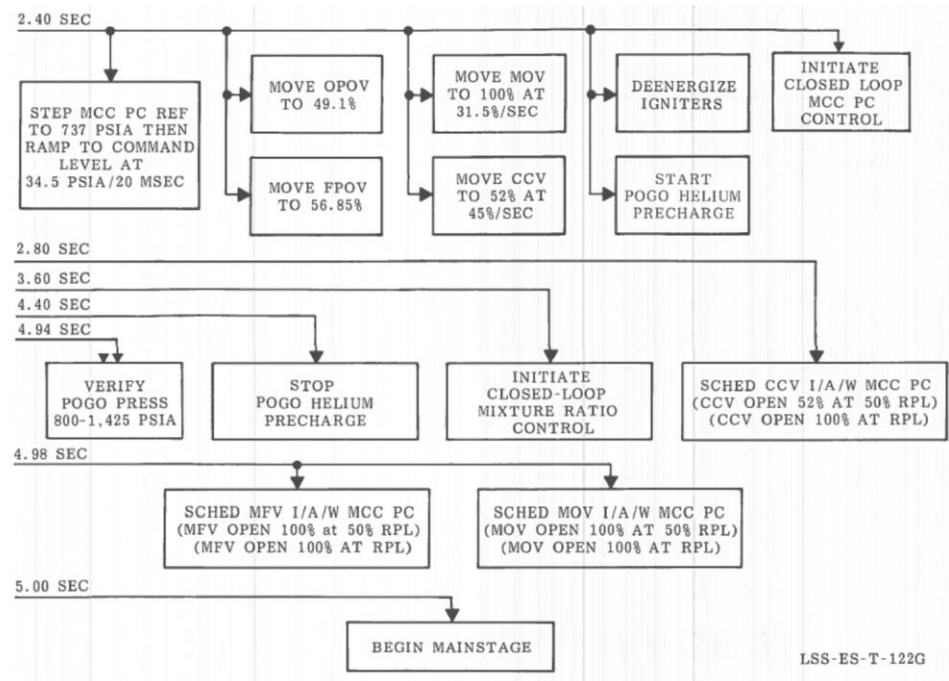


Figure 8. SSME start phase (thrust buildup mode – nominal duration = 2.6 sec).

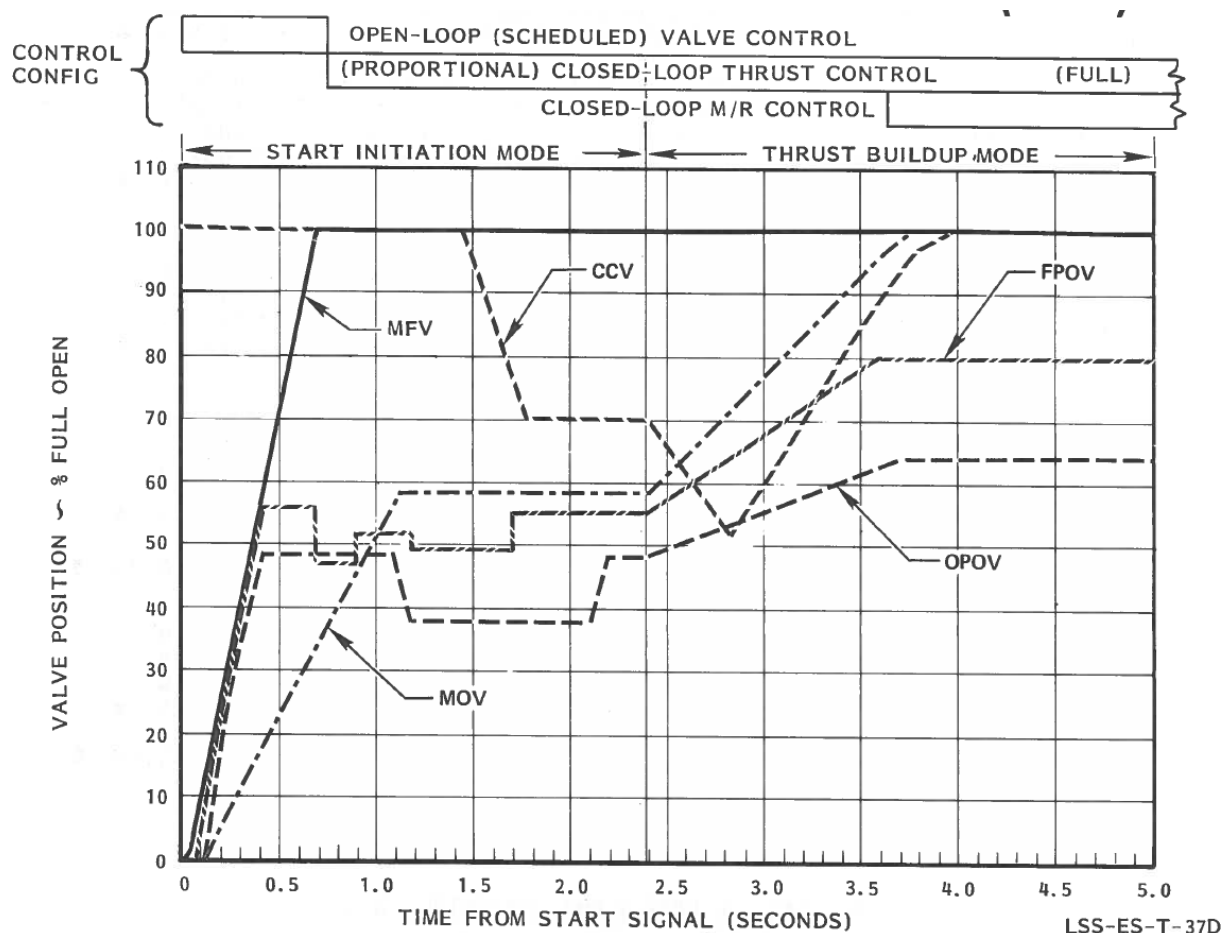


Figure 9. Valve position - % age full open Vs Time from start in seconds (based on signal) .

3. Condensing heat exchangers (CHX)

An important part of orbiter is condensing heat exchanger (CHX). This may be used in thermal and humidity control systems. This may be designed using porous media [11-14]. In essence, it comprises of fin surface which is water cooled to ensure condensation of moist air. It is followed by 'slurper bars' which take in both the condensate (mainly H₂O) and air into rotary evaporator. It is used for separation of water from air. This method provides an attractive alternative of combination of both heat removal and liquid / gas separation into a single unit. A condensing heat exchanger make use of principles of chemical engineering thermodynamics. This involves control of temperature and humidity within an enclosed system (cabin of space craft). It involves study and application of one of four heat conservation processes i.e. isothermal, isobaric, isochoric and adiabatic. Later is mostly applied. Next stage requires mastery of intrinsic properties of a system i.e., sensible heat and heat of vaporization. This involves control and removal of heat generated by power consuming equipment (power electronics), primates and homo sapiens and water vapor and mixture generated by vapors from later.

A more efficient design of condensing heat exchanger involves condensation and removal of water directly from air stream without additional water separator. One such system involves use of capillary action to extract and remove water. Here this phenomenon is represented by high thermal conductivity porous substrate to act as cold surface which collects water by condensation. The thermal properties, the porosity and wetting characteristics of porous material are deliberately chosen such that they promote former with a mechanism (such as a check or no return valve) to prevent reversal, backflow, or suction of water. It is schematically shown in Fig 10 below.

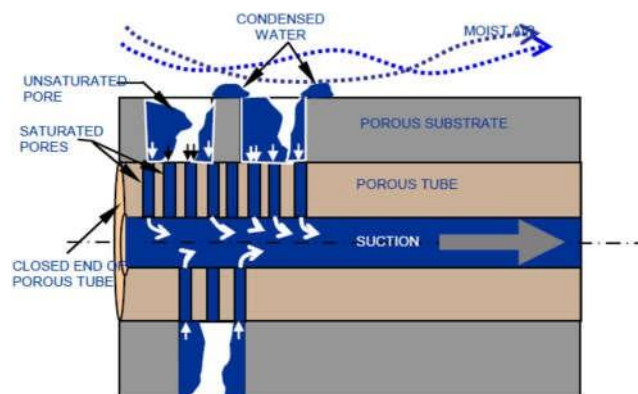


Figure 10. Porous substrate and tubes of varying sizes to remove condensate (transient processes) (not to scale).

Thermophysical properties and fluid flow characteristics of such a system are shown below (Figure 11 – 13).

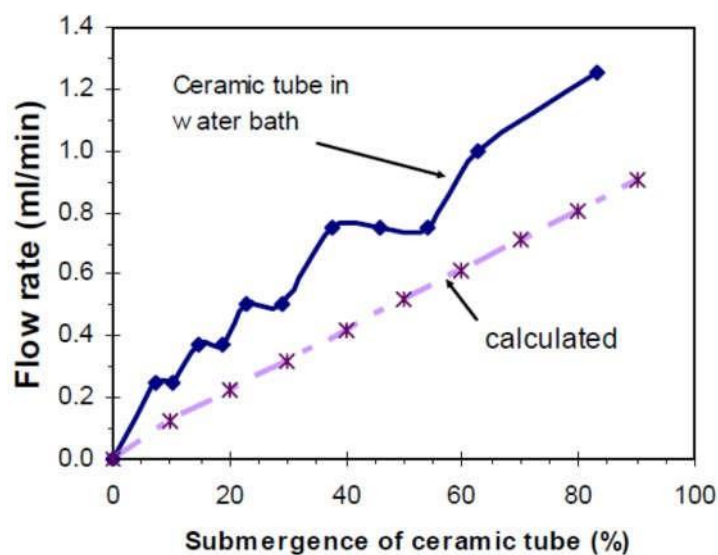


Figure 11. Chart showing flow rate as a function of percentage submerged ceramic tube.

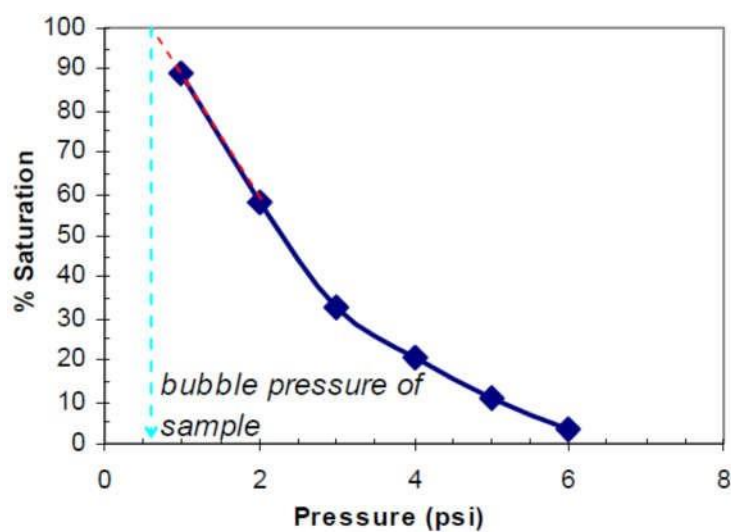


Figure 12. Curve of pressure-saturation PG-45 Graphite.

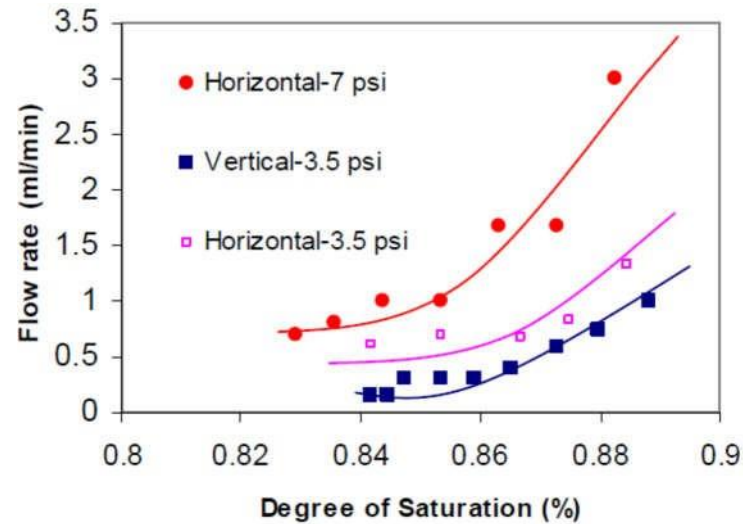


Figure 13. Selective extraction of H₂O from an unsaturated graphite block at horizontal and vertical configurations and orientations.

4. Regenerative heat exchanger (RHX)

An important part of orbiter thermal loop system is regenerative heat exchanger described elsewhere [15, 16]. Regenerative heat exchangers or thermal regenerators [16-18] are type of heat exchangers which make use of waste heat in a system and use it to heat a regenerative system e-g. in the form of storage media such as packed beds or checker works. In other words, these types of heat exchangers transfer heat within gases (from one to another), with by storage in solids. These heat exchangers are used when heat has to be conserved and reused.

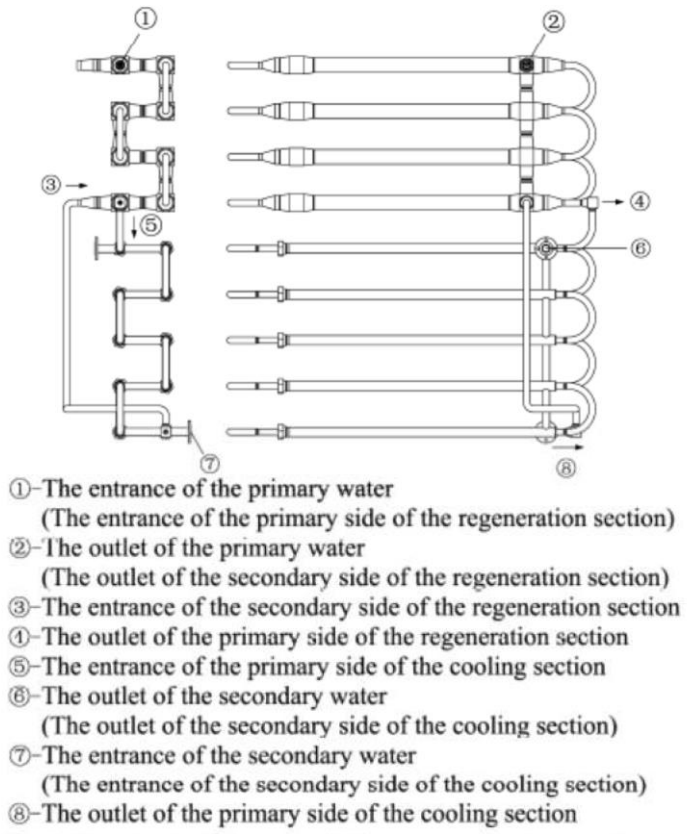


Fig. 1 The structural diagram of the regenerative heat exchanger

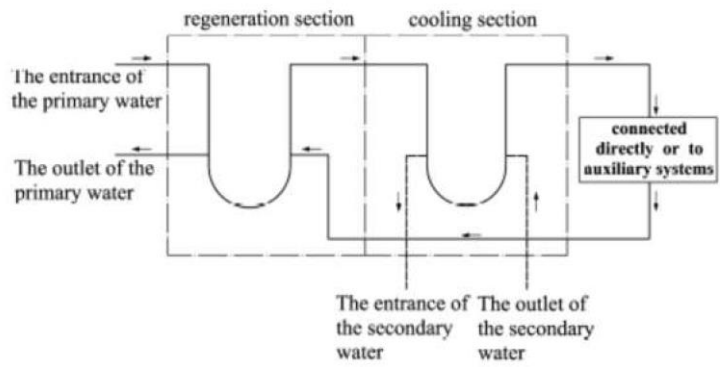


Figure 14. Regenerative heat exchanger.

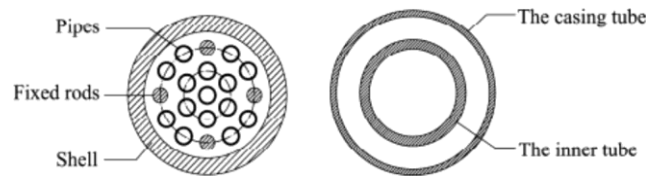


Figure 15. The flow path cross sectional area of cooling section and regenerative section.

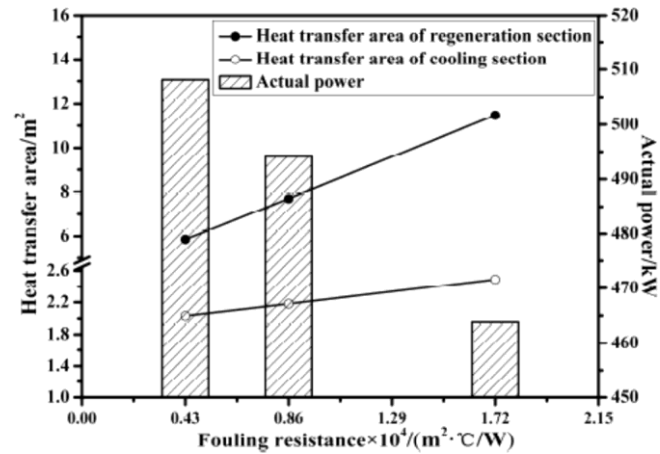


Figure 16. The influence of primary water fouling thermal resistance on the generative heat exchanger.

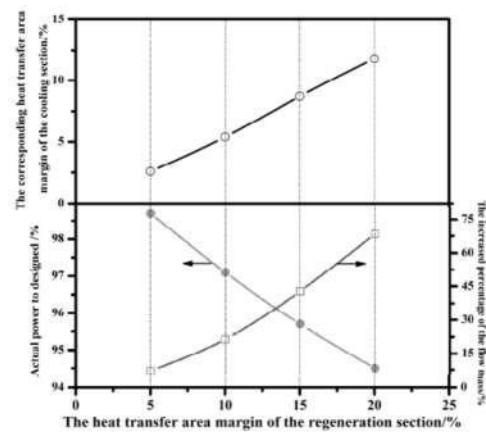


Fig. 6 The effect of regeneration section heat exchange area margin on the generative heat exchanger

Figure 17. The effect of regeneration section heat exchanger area margin on the generative heat exchanger.

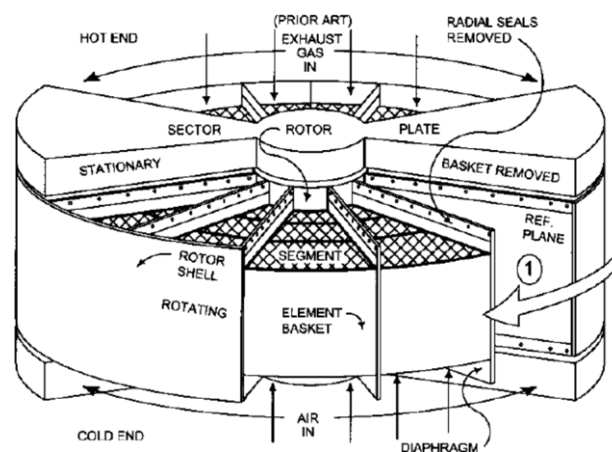


Figure 18. Regenerative heat exchanger.

5. Thermal control system (passive and active)

An important part of space shuttle orbiter is active thermal control subsystem (ATCS) [1, 19]. This consists of series of evaporators and coolers arranged and operated in such a way that they are responsible for maximizing heat transfer from, and to space craft, its

units, and instruments [3, 9, 20]. Flash evaporation is used as a highly efficient and responsive means for Orbiter Freon loops cooling during ascent, descent, and entry. It also provides supplemental cooling while in orbit. Briefly, it consists of below parts.

5.1. Internal heat exchanger

Internal heat exchanger is an important part of space craft. They are installed in heat exchanger complex at a specific location which is discussed elsewhere [2, 3].

5.1. Interface heat exchanger (IHEX)

Operation of orbiter ATCS required advances in the state of art of compact heat exchanger design and manufacture. Fin density, flow configuration and headering research is considerably advanced to achieve optimization. Concentrated efforts are made in the design of these devices to reach minimum weight, volume, and power impact in vehicle (Fig 19 – 23).

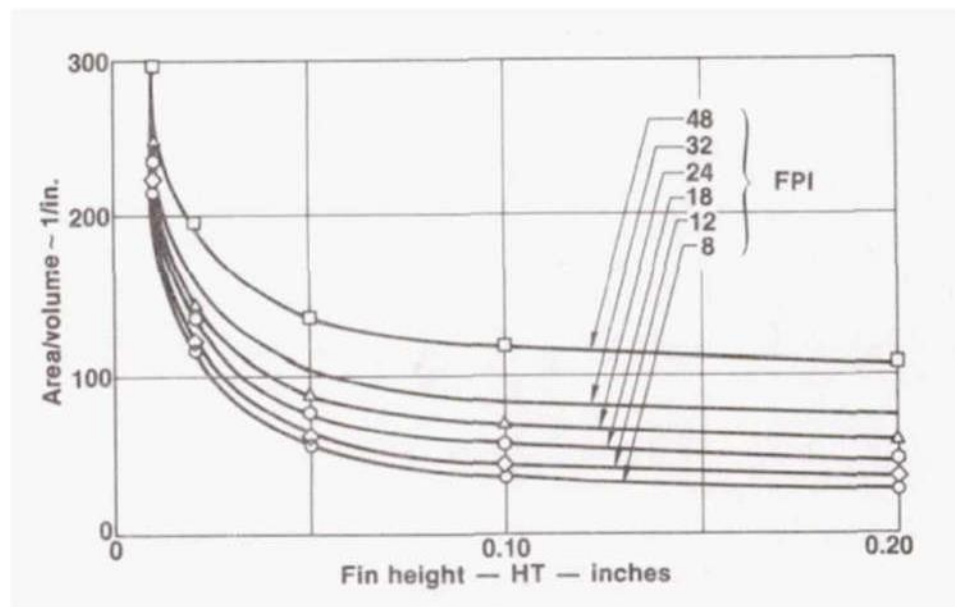


Figure 19. Fin optimization.

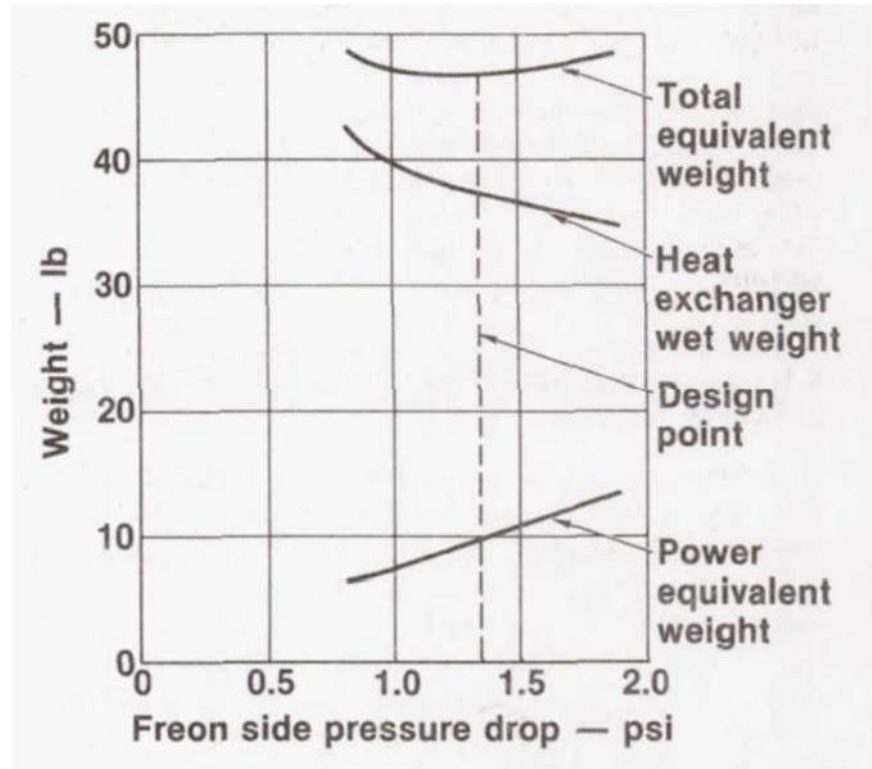
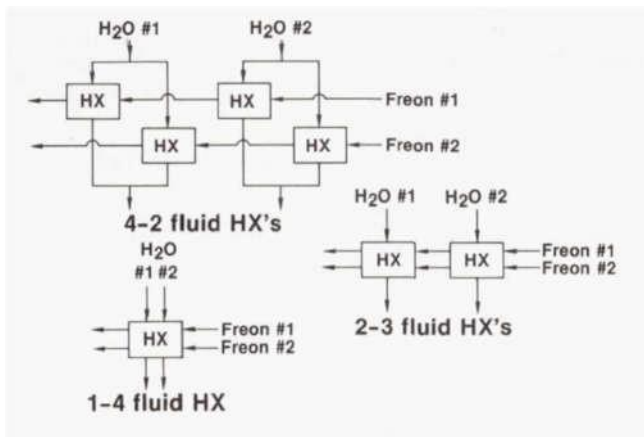
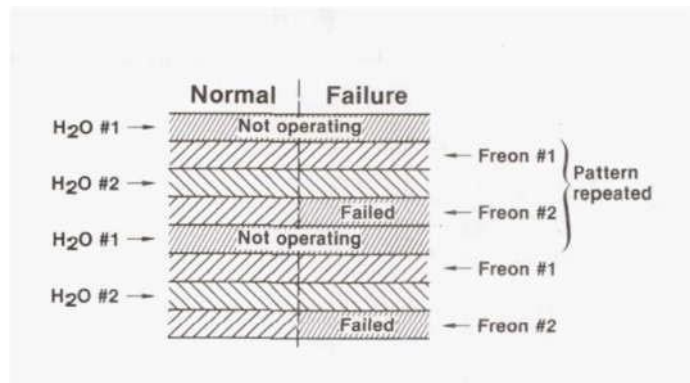


Figure 20. Interchanger optimization.



(a)



(b)

Figure 21. (a) Interchanger candidate approaches and (b) Interchanger layers.

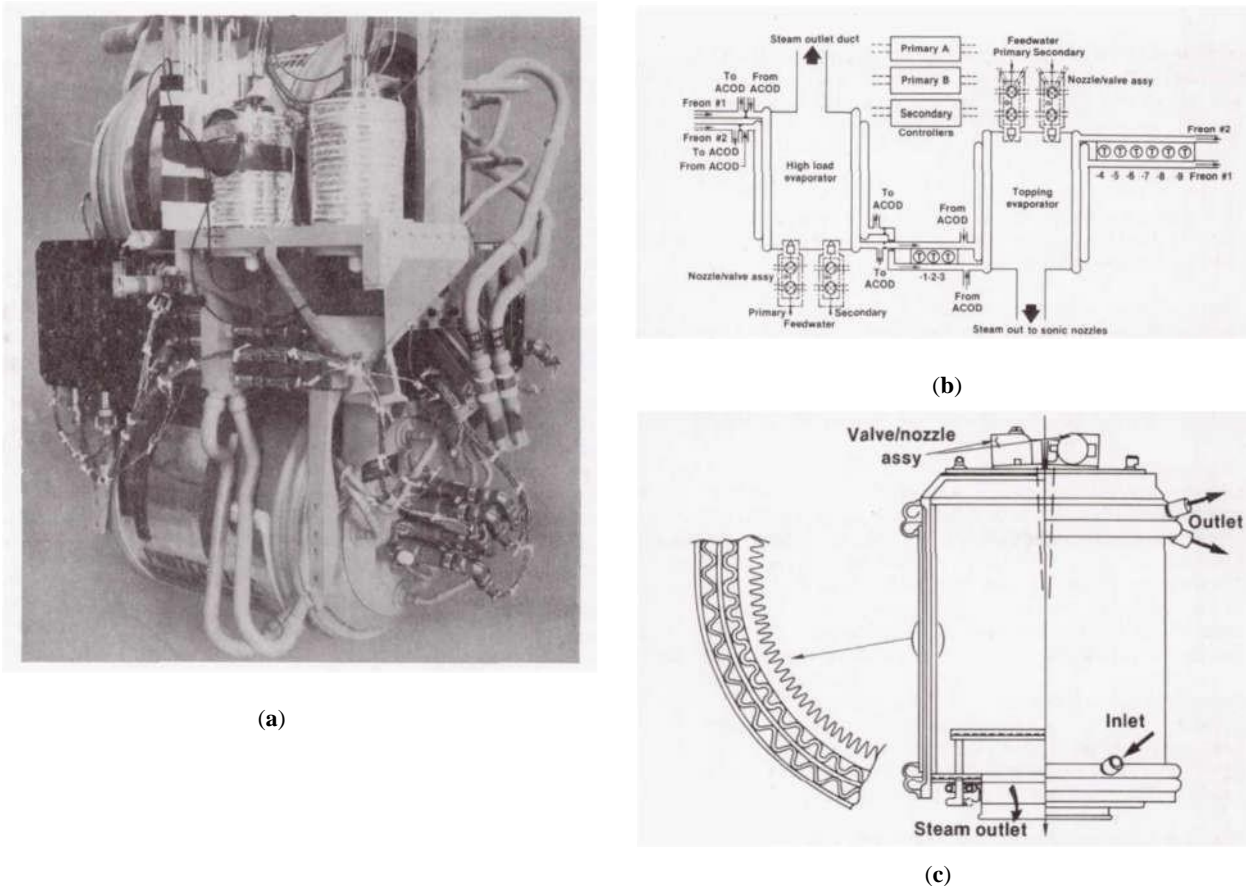


Figure 22. (a) Flash evaporator package (b) Flash evaporator assembly schematic (right hand side top) and (c) Shuttle evaporator (right hand side bottom).

5.2.1. Fin optimization

Heat transfer area divided by core volume (A/V) is the term used to determine compactness of a heat exchanger. This serves both from a weight and volume standpoint [2, 3, 9]. Highest density designs are desirable as they yield lightest and smallest unit to a practical limit. This term is plotted against fin height and number of fins per inch (FPI). Fin heights ranging from 0.010 to 0.200 inches and FPI ranging from 8 to 48 were investigated. It concluded that denser fins yield higher values of A/V (Fig 19).

6. Environment control and life support system (ECLSS)

An important part of orbiter is environment control and life support system (ECLSS). Essentially, for whole mission (consisting of travel to, stay and return from space), it may be divided into two sub systems. On board orbiter related environment control and life support system (ECLSS) and extra vehicular activity (EVA) also known as space suit. Both have their own particular, specific, and individual requirements which must be fulfilled each time in each mission. It has various types such as open loop life support, physiochemical and bioregenerative systems. Interested reader may find their details in bibliography.

7. Conclusion

Heat exchangers play an important role in design (initial design, calculations, front end design (FD), detailed design (DD), re design or wetting, final design), drafting (sketching, 2 dimensional drawings, projections, isometrics, exploded views, rendering and optimization), development, manufacturing, fabrication, installation (pumps, valves, piping and instrumentation (PID)), assembly, maintenance (preventive, predictive, projected, interpolated, extrapolated), operation, performance and yield of high speed turbo

machinery. In Space shuttle main engine, they bear a significant place in main pressure head assembly which is mounted on nozzle with a free rotating needle free gimbal joint. Main combustion chamber is also part of this arrangement intermittent of former and later. It is delicately connected with its vanes to tubing, orifices, protrusions and exists. This nicely increases its efficiency and performance. It is found that its different types (single coil (on exterior), rod type (straight tube), internal, condensing, interface, regenerative and compact) exerts an important impulse or their performance. This is vital for the operation of orbiter and helps in achieving its objectives (transportation of objects from its home planet (earth) to outer space (lower orbit (~ 300 Km)), with modifications, or a new design to neighboring heavenly bodies (e.g. earth's natural satellite (moon) and inner planets of solar system (e.g. Mars)).

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