ME662 Mechanical Engineering Practice

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Thermodynamic Model of Hydrogen Turbine

Group 6

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Abstract:

Performing preliminary analysis of a new hydrogen-driven turbine engine system proposed by an inventor in Topeka, Kansas, Mr. Wilbur Johnson. The inventor believes that a new engine potentially gives aircraft great advantages. Because the engine uses hydrogen as an energy source to drive turbine engine without burning, so the medium is recyclable. He also noted that hydrogen could be extracted from the atmosphere in flight by separating the hydrogen out of water vapor. As result, the airplanes can possibly fly an infinite period of time. The study was done over the conceptual analysis and technical, practical and economical feasibilities.

Acknowledgements:

The team would like to thank all the individuals who lend helping hands over the semester regarding to the project.

- Mr. David Richard, Product Engineer, MAMTC
- Mr. Wilbur Johnson, Inventor
- Dr. T. S. Ravigururajan, Associate Professor, Mechanical Engineering Department, Wichita State University
- Dr. K. A. Soschinske, Instructor & Lecturer, Mechanical Engineering Department, Wichita State University

In addition, there are organizations and businesses, which made information available over the Internet or other published sources.

- The National Aeronautics and Space Administration – Providing information regarding to the hydrogen powered turbine development.
- The United States Department of Energy – Providing the background information about the hydrogen and its use as a source of energy, and the price information
- The University of Florida – Hydrogen propertied package, which used to determine the properties of the hydrogen at certain stages.

Table of contents

List of Figures

List of Tables

1. Introduction

1.1. Problem:

An inventor Mr. Wilbur Johnson brought a proposal of a new turbine engine design and wants to know if the design is feasible. The concept of this turbine is to acquire kinetic energy from the high-pressure hydrogen gas, expanded from liquid by addition of heat, which is from outside of the system. This technology allows turbine to run without its compressor stage and there are no emissions. Thus, the system is able to recycle hydrogen from the exhaust part of the turbine.

1.2. Objectives:

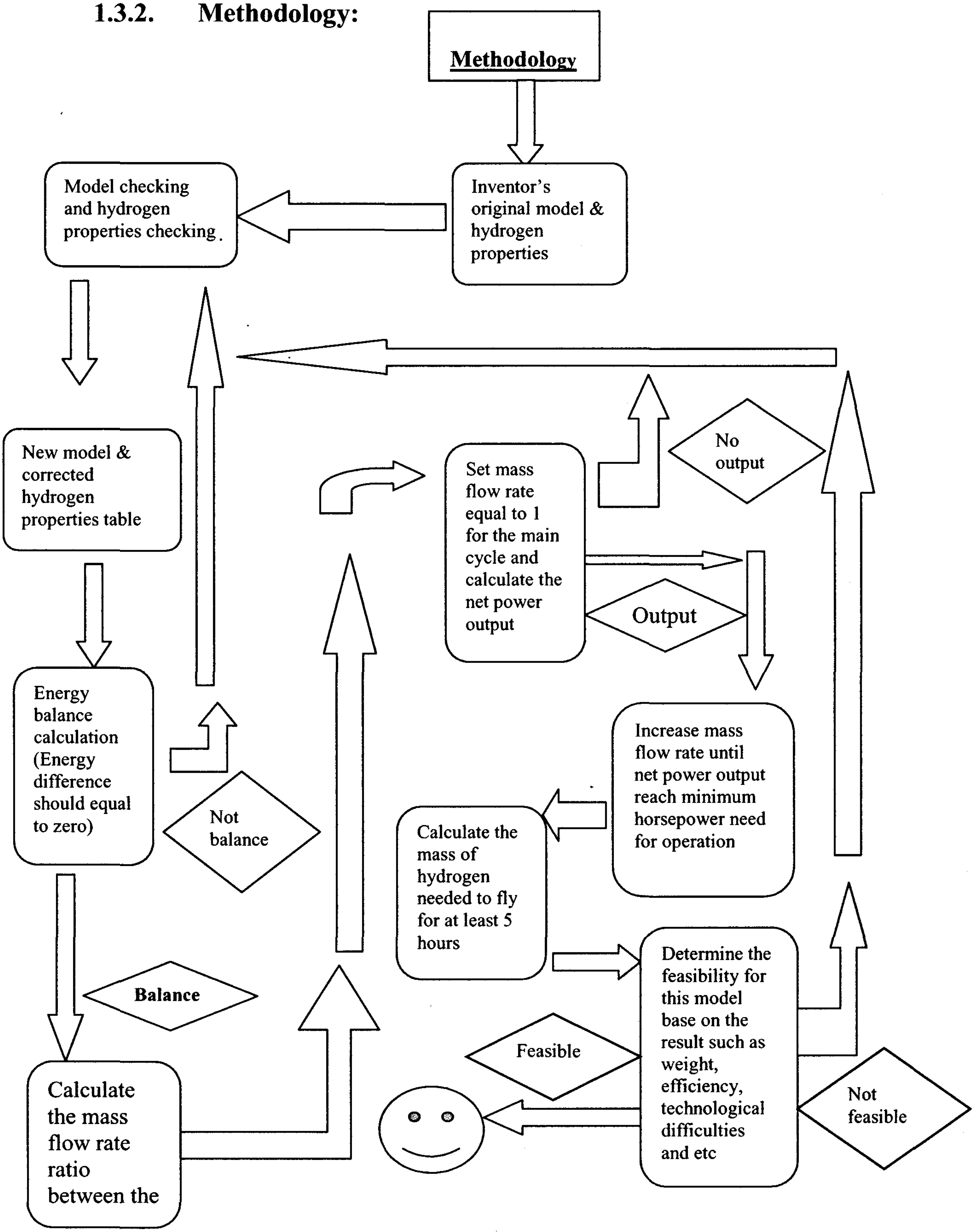
The objectives of this project are to investigate the characteristics of the system and to determine if the new hydrogen turbine system can be comparable with regular fossil fuel powered turbine engine, and to study potential product liability issues for this case.

1.3. Approach and Methodology:

1.3.1. Approach:

1. Gather the information related to the project
   a. Understand the mechanism of the proposed system and its concept
   b. Study the properties of hydrogen
   c. Search for small commuter airplanes and their specifications
   d. Search for the turbine engines used in small aircraft
   e. Look for hydrogen turbine projects worked in the past
2. Make a mathematical model of the concept model and perform further studies
   a. Set up energy equations of the system
   b. Determine if the model proposed by inventor follow thermodynamic laws
   c. Correct the settings of the system proposed by the inventor
   d. Determine the performance of the system
   e. Try other several cases to see if any improvements can be made
3. Compare performance with turbine engines
   a. PT6A-60A turbo-prop engine
   b. Model 304 hydrogen turbine engine
   c. The engine proposed
4. Evaluate the design and conclude the feasibility
   a. Economical Feasibility
   b. Environmental Feasibility
   c. Technical Feasibility
5. Issues of expected in case after production (Product Liability)
   a. Materials
   b. Turbines, Pumps, Storage tank and Heat exchanger
   c. Safety Issued regarding to the Cryogenic Condition

1.3.2. Methodology:



2. Results

2.1. *Design Criteria:*

The design proposed contains more than one item. The components are not only the turbine, but also pumps, heat exchanger and condenser. All of the items must be carefully evaluated to see if the components' function and the necessity of the items.

Mr. Richards, who sponsored this project, suggested several items. First, the design may not be suitable for jet engine since the gas must be recycled. Second, the values considered should not be trusted since there are very little resource available for cryogenic condition of hydrogen gas or any other turbine system used in the past.

This engine requires these conditions:

- Able to produce large power output which is comparable to the conventional turbine engine from the system (1,000HP)
- Able to operate under extreme condition in temperature, moisture or other weather conditions including the wind or dust
- Able to satisfy the conditions above without consuming or losing the hydrogen from the system.

2.2. *Functional Design Criteria:*

The aviation power plant requires lightweight and high power output. In general, reciprocating engine weighs about 0.5 to 1.0 kg for each horsepower generates. For the turbine engines they are about 0.15 ~ 0.50 weight (kg) / thrust (kg) for turbo jet engine, and 0.10 ~ 0.30 weight (kg) / SHP (shaft horsepower) for the turboshaft engine.

The Jet-A fuel powered PT6A-60A, used as the power plant for Beechcraft Super King Air 350, is a typical upper level turbo prop engine. The Super King Air was developed in the 1960s, and has been one of the best selling twin turbo propped airplane. The engine weighs about 460 lb, 6.0ft long and 1.7ft diameter. It generates about 1,050SHP (shaft horsepower) at maximum.

Materials for the components used in the system must be determined. The material can be used in this system must show good resistance with corrosion by hydrogen and maintains its strength at cryogenic condition. Most of metals become brittle as the temperature decreases, losing its elasticity. There must be some trade offs and need to be balanced.

2.3. Brainstorming and Conceptual Design:

2.3.1. Engines Used in Aviation Industries:

There are several power plants used in aviation.

1. **Reciprocating engine** – same as regular power plant used in automobiles. Uses gasoline or diesel fuel and burn with air to produce energy. Although it is possible to burn hydrogen to produce the same energy. This configuration does not satisfy the idea not to burn hydrogen.

2. **Turbojet engine** – Uses fossil fuel to turn the turbine system by creating high-pressure gas. The engine consists of diffuser, compressors and a burner. The compressor is driven by using a part of the energy from the turbine. Most of thrust will be generated by displacing the air in front of the engine to behind of the engine. The energy produced by combustion is not a large part of the total thrust.

3. **Turbo-prop engine** – drives propellers by the power produced from a small turbine engine. The propellers produce about 85% of the thrust, and the exhaust of the turbine will generate other 15%. Since the engine proposed by the inventor has no exhaust, this maybe a good candidate since the engine unit is concealed.

4. **Turbo fan engine** – a turbo jet with another set of turbine, which produces thrust. The fuel consumption is about 40% less than the turbojet. This may be a good idea for the proposed turbine since the turbine system is contained in an internal part of the engine. However, system is much more complicated than any of engines above.

5. **Ram jet engine/ SCRAM jet engine** – Both engines do not have compressor stage since they use the forward motion to get the air into the engine compartment. Most of the time they use hydrogen as a fuel in the combustion chamber since there will be no metal to be melt by the extremely high temperature. This kind of system is applicable only for supersonic cruise ($M=1^+$).

2.3.2. Background Information Related to Hydrogen Turbine:

1. Hydrogen Turbine for Submarines

During the World War II, German tried to use a turbine system runs on the mixture of hydrogen peroxide and diesel. Submarines were operated by either battery or diesel powered. However, there is a limited amount of air can be contained inside of a submarine, so they needed a way to feed oxygen under the water without using snorkel. Several prototypes were made but none entered combat. This turbine uses hydrogen peroxide and diesel fuel to produce hot, high-pressure steam. After the WWII, many other countries tried this approach, but none entered actual service since the method is too dangerous.

2. Stirling Engine

The Stirling Engine is powered by the expansion and compression stage of gas. Once gas was expanded by heat, it raises pressure therefore work can be done. By transferring the heat to another cylinder, the first chamber can be cooled down and the volume decreases. Although it seems perfect power plant, cylinders must be transferring the heat quickly. In reality, it takes while to cool or warm a large volume of the gas, so it must be used on smaller power plant. Thus, not large energy output cannot to be expected.

3. Hydrogen Turbine for Aircraft

One of the projects NASA worked on during the 1960s included a development of hydrogen-powered aircraft. Since thermal efficiency of hydrogen combustion process increases as the altitude increase. The project was aimed to develop hydrogen turbine engine for high altitude flying .aircraft. No concept actually took off, but several experimental engines were made. One of them is coded as model 304. Specific information can be found in appendix.

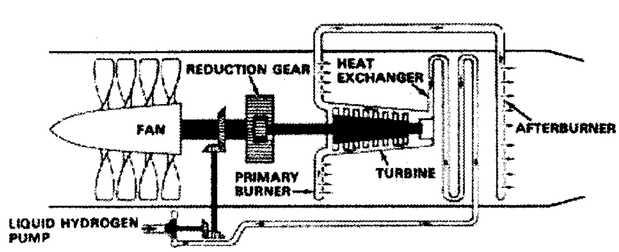


Figure 1 Model 304 Engine

4. Hydrogen Turbine for Modern Aircraft

The Daimler Aerospace is developing a hydrogen-powered airliner. This airplane uses conventional turbofan engines modified for hydrogen fuel. Most of the gas will be stored on top of the fuselage as seen the picture below. There is also a project to develop a smaller commuter jet plane, which carries hydrogen tanks under the wings.

Figure 2 CRYOPLANE

The Boeing Aircraft Company also has a plan to develop an airliner with hydrogen-powered turbines. There is no specific information available up to date.

2.3.3. Fuel Selection:

If the hydrogen is burned, it generates about 120,000kJ/kg, comparing the fossil fuel generates only 42,800kJ/kg. The hydrogen is also shows good characteristics as heat absorbent.
Another good reasons of using hydrogen are its availability. The hydrogen can be produced by separating water into hydrogen and oxygen. While fossil fuel is irreplaceable, hydrogen can be produced from the vast amount of water which is almost an infinite resource. Moreover, requiring no combustion process is good for the environment.
The disadvantages of using hydrogen as fuel are problem with storage and it can corrode metal which can drastically reduce the service life span. In addition, the system proposed might have to be operated under cryogenic condition which the most of material loses its elasticity and the strength.

2.3.4. Turbopump Used in a Rocket Engine:

The space shuttle orbiter has three rocket engines which equip turbopumps. The engine weights about 7,500lb, and produces approximately 420,000lb of thrust from combustion. The hydrogen is stored at the temperature of -423°F, and delivered through a turbopump at rate of 160lb per second, the injection pressure of the hydrogen will be raised up to 6,200psi. The turbopump will be driven by the expanding liquid hydrogen. The bearing of the system uses silicon nitrate.

2.3.5. Aircraft Information:

Beechcraft Super King Air 350 is designed in 1960s and has been one of the best selling turbo-prop aircraft which can be rated as commuter aircraft.

SPECIFICATIONS:	
Wing Area and Loadings	
Wing Area	310 sq ft
Wing Loading	48.4 lb / sq ft
Power Loading	7.14 lb / shp
External Dimensions	
Wing Span	57 ft 11 in
Stabilizer Span	18 ft 5 in
Length	46 ft 8 in
Height to Top of Horizontal Stabilizer	14 ft 4 in
Pressurization	
(6.5 PSI Differential)	Cabin Altitude
Actual Aircraft Altitude 15,293 ft	Sea Level
Actual Aircraft Altitude 29,742 ft	8,000 ft
Actual Aircraft Altitude 33,400 ft	10,000 ft

WEIGHT/PAYLOAD:	
Weights	
Maximum Ramp Weight	15,100 lb
Maximum Take-Off Weight	15,000 lb
Maximum Landing Weight	15,000 lb
Maximum Zero Fuel Weight	12,500 lb
Basic Operating Weight	9,640 lb
Useful Load (Standard Airplane)	5,460 lb
Maximum Fuel (539 gal at 6.7 lb / gal)	3,611 lb

POWER PLANT	
General	
Manufacturer and Type	Pratt & Whitney PT6A-60A Reverse Flow
Take-Off Thrust	1,050 shp

RANGE	
Allowance:	Start, Taxi, Take-Off, Climb, Cruise, Descent, NBAA IFR Reserve Profile (100 nm Alternate)
Loading:	1 Pilot (@ 200 lb), + 4 Passengers (800 lb Payload), Full Fuel
Conditions:	Zero Wind, 9,440 lb Empty Weight, 13,986 lb Take-Off Weight
Normal Cruise Power (1,500 rpm)	
16,000 ft	943 nm (1,085 sm)
22,000 ft	1,107 nm (1,274 sm)
28,000 ft	1,321 nm (1,520 sm)
35,000 ft	1,597 nm (1,838 sm)

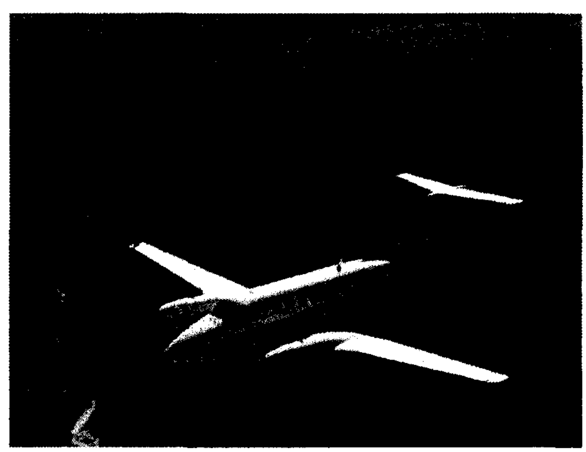


Figure 3 Super King Air 350

From Raytheon Aircraft Co. Web page

2.4. Preliminary Analysis:

2.4.1. System Analysis

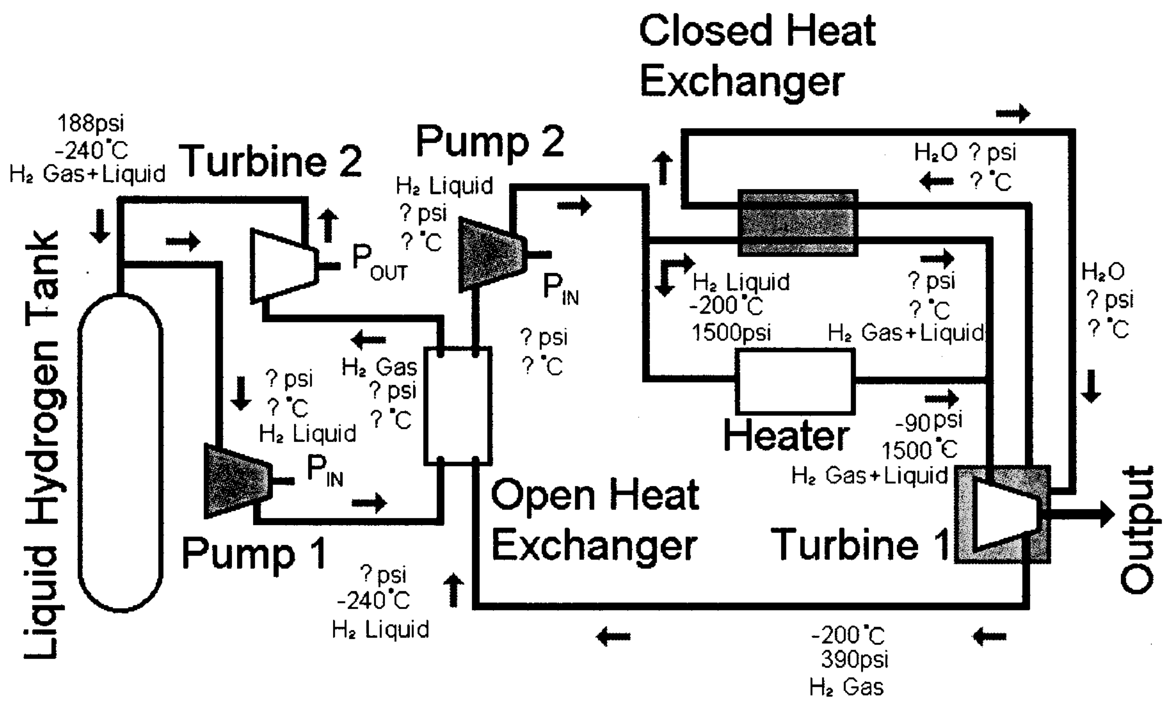


Figure 4 Original Model

The system consisted of two pumps, two turbines, one heater, one closed heat exchanger, one open heat exchanger, and a liquid hydrogen tank. The left hand side of the system serves as a refrigeration system and also the source of fuel. The aircraft receives heat from either outside through the heater or closed heat exchanger. The heater can be installed at surface of the wing, or between upper and lower surface of the wing. The hydrogen will be expanding as it passes heater then drives the turbine 1. The heated hydrogen, now in the gas form will be chilled at the open heat exchanger. The closed heat exchanger on the right upper side generates heat by combustion while the outside air cannot provide enough heat into the system.

2.4.2. Feasibility Analysis

1. Technical Feasibility

    a. Rapid Chill of the System

    To set up the system, the whole components must to be cooled to certain temperature before it become operational. It is not good idea to fill liquid hydrogen in to a tank of room temperature since the tank can contract rapidly, and may cause cracks. NASA has studied this subject and it is possible to fill the liquid hydrogen tank quickly by putting cold hydrogen gas to cool the container prior to the filling process.

    b. Weight of the Tank

    Weight of the container ($1/10^{th}$ of the weight of the tank according to the NASA's approximation in the Suntan project). Unlike aviation fuel, hydrogen has very low density and has to be compressed at very high pressure and at low temperature to keep the hydrogen in liquid form. There are very few materials available for this kind of purpose, but some composite tank can hold pressurized, super cooled hydrogen.

2. Economical Feasibility

    a. PT6A-60A Turbine Engine

    This engine consumes about 1,000lb of jet fuel each hour, the engine proposed should not exceed this value in order to be comparable,

    b. Fuel Consumption rate

    The price of aviation fuel is about $1.50 per gallon. One gallon of fuel weight about 2.5 pounds. Considering this number as reference, it is possible to compare with the price of hydrogen per mass. In general, the price of liquid hydrogen ranges from $0.50 to $1.00 per pound. Thus, the price of the hydrogen as fuel is very competitive. However, hydrogen may shift its phase during the storage and has to be treated before filling. The current model loses hydrogen about 40,000lb/hr so the running cost of the engine is about $20,000~$40,000 per hour, while running the PT6A-60A costs only $600.

3. Environmental Feasibility

    Hydrogen is a recyclable energy source. The hydrogen can be separated from water by electrode. When react with oxidizer, it produces only water. This will not pollute air.

2.4.3. Technical Problems and the Solutions

1. The table with mixture states of hydrogen is not allowed.

   Reasons:
   - Turbines can only intake gas and outlet gas.
   - Pumps can only intake liquid and outlet liquid.

2. Open heat exchanger that links the main cycle and sub cycle together is not going to work.

   Reasons:
   - The inlet of the open heat exchanger should be gas from the main cycle and liquid from the sub cycle. The outlet of the open heat exchanger should be liquid to the main cycle and gas to the sub cycle. Without applying different pressure on both cycles this target cannot be achieved. Open heat exchanger cannot provide a different pressure situation, but closed heat exchanger is able to do so.
   - Even we ignore above reason the calculation of the open heat exchanger with mix of gas and liquid is still not possible.

3. Condenser needed in the sub cycle.

   Reasons:
   - For calculation of energy balance equation.
   - For recycling purposes.

4. The engine shroud recommended to be removed.

   Reasons:
   - It is only an additional device for the system.
   - In order to determine the feasibility of this system, we need to simplify this system into the most basic model.
   - The energy balance equation is needed for the engine shroud if we include it into the system. However, the energy balance equation for this engine shroud can only be determines only after the energy balance equation of the main and sub cycle is determined.

<u>Solutions (Changes been made):</u>

- Table of the hydrogen properties has been changed. No mixture state.
- Open heat exchanger has been changed to the close heat exchanger.
- Engine shroud has been removed.
- The system has been simplify to two Rankine Cycle without changing the major functions of the whole system.

2.4.4. Rankine Cycle

Rankine Cycle is the model for the simple steam power plant. It is convenient to show the states and processes on a T-S diagram. The four processes are:

1-2: Reversible adiabatic pumping process in pump
2-3: Constant-pressure transfer of heat in the boiler
3-4: Reversible adiabatic expansion in the turbine
4-1: Constant-pressure transfer of heat in the condenser

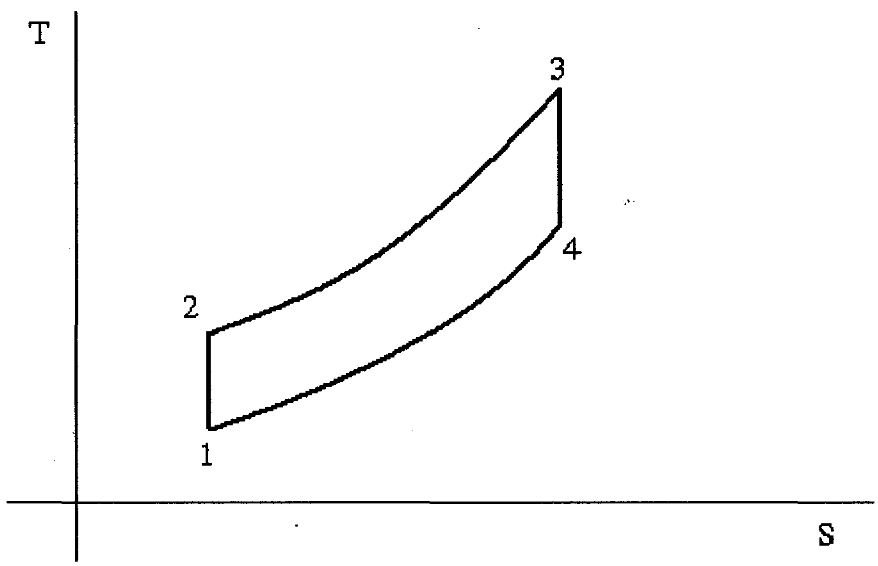


Figure 5 Rankine Cycle T-S diagram

A simple model of Rankine Cycle can be shown as below:

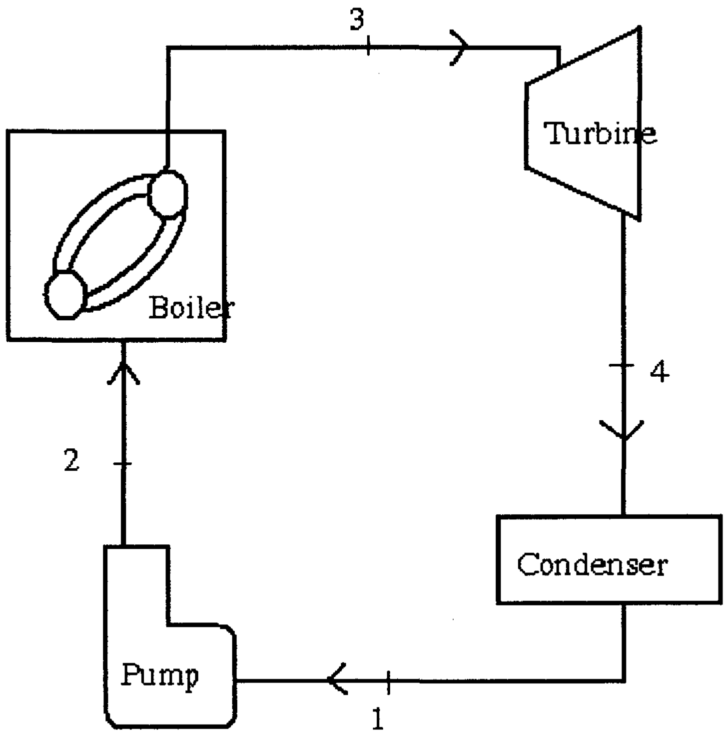


Figure 6 Basic Rankine Cycle Model

<u>The Four Basic Component In Rankine Cycle:</u>

~Pump - takes liquid and increase the pressure of liquid.
~Boiler - provides heat to liquid to change it into gas form (superheated).
~Turbine - takes gas and generates power from the pressure drop of gas.
~Condenser - cools gas down into liquid form again for pumping.

The Thermodynamics Hydrogen Turbine model of the inventor can be simplified into a double Rankine Cycle model. Each cycle is a separate Rankine Cycle that combines together. This is the basic form of the inventor's model.

2.4.5. Product Liability Issues

In order to ensure the safety of product during its service life, the manufacturer must be able to provide information about possible hazards at misuse or by other natural causes. The engineers should prepare and determine the worst cases during the development stage, and if possible, changing the method of approach.
This particular kind of system requires considerations in these parts.

1. Turbines, Pumps
2. Handling Hydrogen
3. Hydrogen Tank
4. Heat Exchanger

Turbines, Pumps:

Both turbines and pumps maybe operated under high-speed rotation, so the device and the components must be designed precisely and with great care. Since the system uses hydrogen as the medium, there are some additional considerations must be made.

1. Hydrogen can cause a phenomenon called "Hydrogen Assisted Crack" which is caused by contact of hydrogen to the metal surface, making the metal to become more brittle. Loss of elasticity can result in permanent deformation and faster crack propagation.
2. Hydrogen can also corrode metal, surface coating or use of carbon composite material is recommended. When the impeller becomes corroded, it must be replaced.
3. High rate of rotation of impellers requires a precise balance on the system. Even a slight imbalance in the system can cause vibration, which can cause damage to the parts.
4. All high-speed operating parts require good lubrication. Lack of lubricant can cause contact between parts, since hydrogen is flammable, even a spark can cause explosion.

Hydrogen:

Liquid hydrogen is at very low temperature, and can be explosive. In this system, cryogenic condition of hydrogen can be serious hazard for people who work on the aircraft, refueling, or passengers in case of crash or other accident. In addition, there are possibilities that the joints or other connecting parts, even a component can leak hydrogen gas to the outside. Which can cause accident if any fire or spark is present.

Hydrogen Tank:

The container of the hydrogen must have safety features that not jeopardize the situation in case of accident. In flight, turbulence can create load to the tank, or the vibration can damage the tank or its joint. Moreover, lightning strike can cause catastrophic damage so the tank must be covered with steel wire to redirect electric current. There is no report available at this date about this kind of study. Use of carbon fiber reinforced plastics in composite vessels is recommended. Especially for cryogenic condition

Heat Exchanger:

In the concept, heat exchanger will have a large temperature difference. Since the hydrogen inside of the heat exchanger is well below freezing temperature, it is possible that ice can accumulate on the surface of the system, thus the heat exchanger loses its capability. The other problem is the hydrogen assisted crack. Since the heat exchanger uses many pipes to maximize the heat flux receiving, a chance of getting damage on the piping is very frequent. The hydrogen can be lost very rapidly if any damage occur. Of course, crack can be propagated quickly as hydrogen increases the speed of progress.

Others:

- Disposing a low temperature hydrogen gas can create ice at the exit, which may fall on to people on the ground.

2.5. *Prototype Fabrication:*

To investigate the performance of the new concept, several different models, including the original model, were evaluated. Each model has the thermodynamic equations, description of the system, schematic, calculations and a table of properties at each state. The objective of this stage is to find the best setting for the maximum output with the turbine system without combustion of hydrogen.

2.5.1. Thermodynamic Equations for Original Model

Conservation of mass:

Between the heater and the closed heat exchanger:

$$x_1 * \dot{m}_1 (in) = (x_2 * x_1) * \dot{m}_{HX} + (1-x_2) * x_1 * \dot{m}_{HEATER}$$

In the open heat exchanger

$$\dot{m}_{1g} + \dot{m}_{21} = x_1 * \dot{m}_1 + (1-x_1) * \dot{m}_2$$

Work equations:

Work output of turbine for cycle 1:

$$Wout = x_1 * \dot{m}_1 * (h_{out} - h_{in})$$

Work output of turbine for cycle 2:

$$Wout = (1-x_1) * \dot{m}_2 * (h_{out} - h_{in})$$

Work input through the pump foe cycle 1:

$$(W_{in}) = x_1 * \dot{m}_1 * (h_{out} - h_{in})$$

Work input through the pump foe cycle 2:

$$(W_{in}) = (1-x_1) * \dot{m}_2 * (h_{out} - h_{in})$$

Heat transfer equation:

Heat Loss Due to heat Exchange in the open heat exchanger:

$$Q_{Loss} = x_1 * \dot{m}_1 * (h_{in} - h_{out})$$

Heat gain from outside air:

$$Q_{IN} = (1-x2) * x1 * \dot{m}_1 * (h_{out} - h_{in})$$

Heat gain to the secondary cycle:

$$Q_{Gain} = (1-x_1) * \dot{m}_2 * (h_{in} - h_{out})$$

Heat gain result in condensing the steam:

$$Q_{Gain1} = (x_2 * x_1) * \dot{m}_{HX} (h_{out} - h_{in})$$

Energy balance equation:

$$E_{IN} + E_{OUT} = E_{GEN}$$

$$W_{turbine} + Q_{heat\ sources} - W_{pump} - Q_{heat\ exchanger} = E_{GEN} = 0$$

Efficiencies:

Efficiency of the turbine $= W_{Actual}/W_{Theoritical} * 100$

Efficiency of the pump $= W_{Actual}/W_{Theoritical} * 100$

2.5.2. Evaluation of the Original Model:

Description:

This is the model proposed by the inventor, in order to evaluate the system, there were several problems. The pump and turbine cannot take mixed state of hydrogen, and the open heat exchanger should not take both gas and liquid state of the hydrogen. Therefore, the only energy equations are made.

System Schematics:

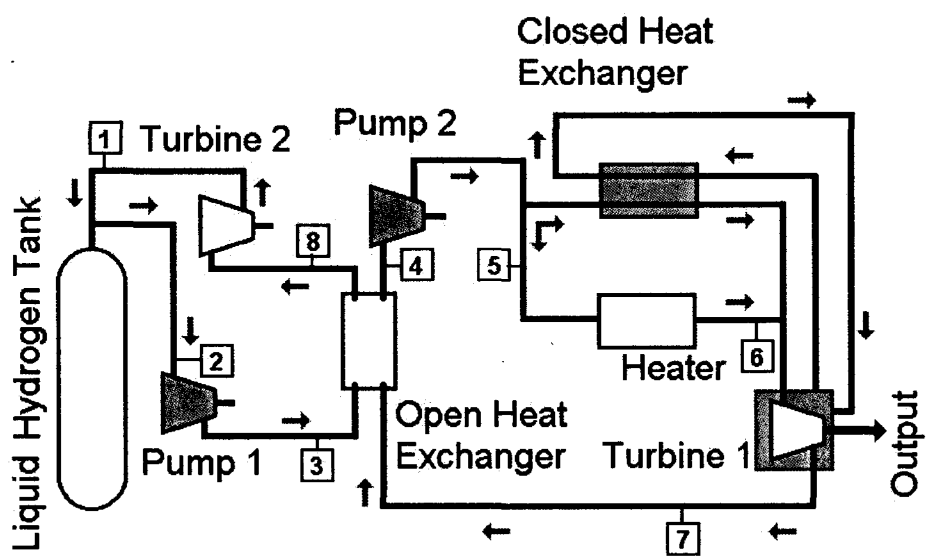


Figure 7 Schematics of Original Model

Table 1 Hydrogen Property Table for the Original Model

Stage	P (psi)	T (°F)	ρ (lbm/ft³)	h (Btu/lbm)	s (Btu/lbm °R)	State
2	188	-400	1.568	192.8	7.171	Mixed
3	390	-400	3.489	28.99	3.229	Liquid
4	390	-410	4.095	65.78	2.559	Liquid
5	1500	-320	1.988	274.00	5.646	Liquid
6	1500	-130	0.792	1027.00	9.013	Mixed
7	1500	-130	0.792	1027.00	9.013	Mixed
8	390	-320	0.543	323.00	7.256	Gas
1	390	-400	3.489	28.99	3.229	Mixed

T-S Diagram:

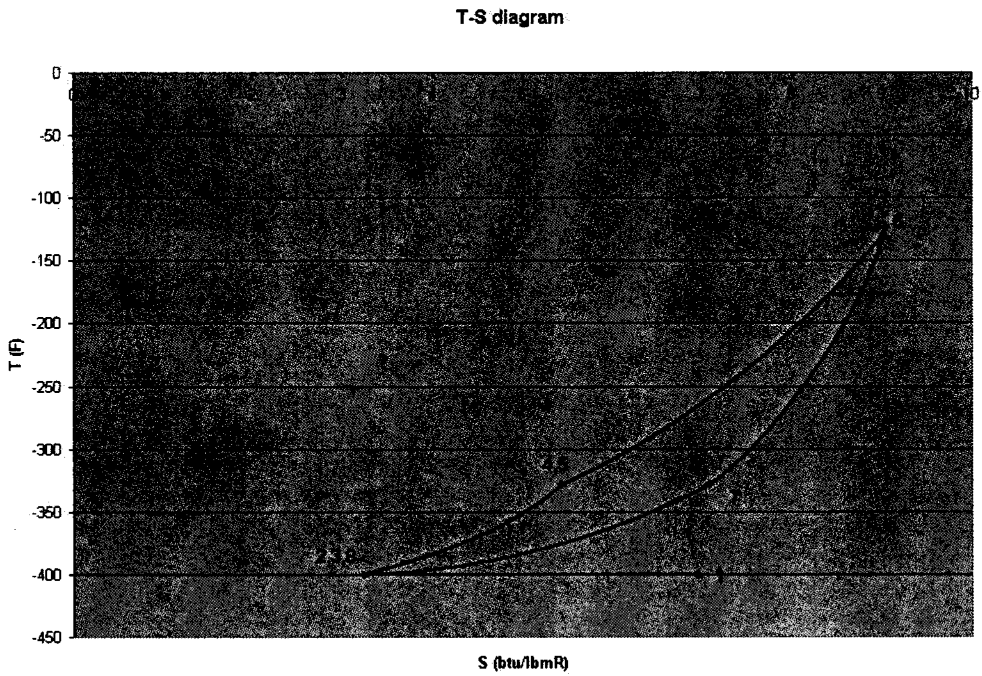


Figure 8 T-S Diagram of the Original Model

2.5.3. Thermodynamic Equations for Model 1

Conservation of energy

$E_{IN} - E_{OUT} = \Delta E$
$\Delta E = W_{turbine} + Q_{heat\ exchanger} - Q_{heat\ sources} - W_{pump} = 0hp$

Thermodynamic Equation

Main Cycle

- State (5-6): Work input through the pump
  - $Win = m*(h_6-h_5)$
- State (6-7): Heat gain from outside air
  - $Q_{IN} = m*(h_7-h_6)$
- State (7-8): Work output of turbine
  - $Wout = m*(h_7-h_8)$
- State (8-5): Heat Loss Due to heat exchange
  - $Q_{Loss} = m*(h_8-h_5)$

Sub Cycle

- State (1-2): Work input through the pump
  - $Win = m*(h_6-h_5)$
- State (2-3): Heat gain from the sub-cycle at Heat exchanger:
  - $Q_{Gain} = m^{\cdot}*(h_3-h_2)$
- State (3-4): Work output of turbine:
  - $Wout = m^{\cdot}*(h_3-h_4)$
- State (4-1): Energy needed for condenser:
  - $Q_{cond}= m^{\cdot}*(h_4-h_1)$

2.5.4. Evaluation of the Model 1 (Ideal Cycle)

Description:

The simplified model uses two Rankins cycles. Since the system is completely separated, the calculations were done for both sides. A closed heat exchange replaced the open heat exchange in the original model to able the calculations. In addition, a condenser was added for the left hand side of the system to complete the Rankine cycle so the hydrogen can be liquefy again.

Schematics of Model 1

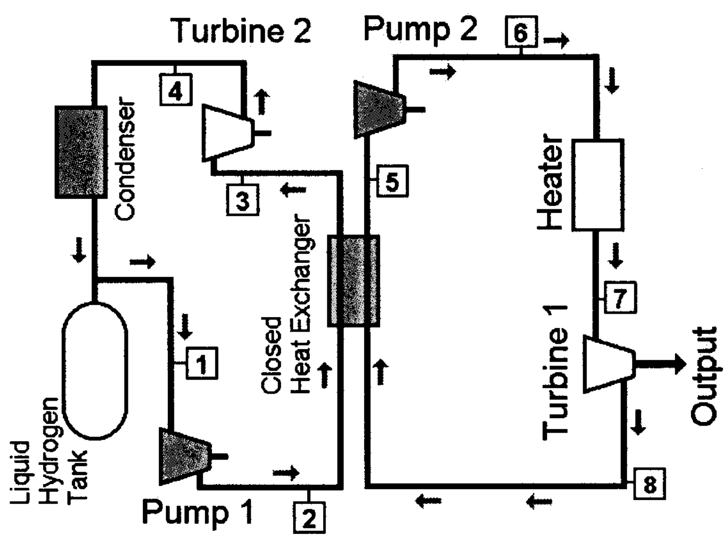


Figure 9 Schematics of the Model 1

Equations:

Conservation of energy equation:
Main Cycle:

$E_{IN} - E_{OUT} = \Delta E$

$\Delta E = W_{turbine} + Q_{heat\ exchanger} - Q_{heat\ sources} - W_{pump}$

$= 304hp + 511.4hp - 700.7hp - 114.4hp \quad = 0hp$

(conservation of energy is proven all right)

Sub Cycle:

$E_{IN} - E_{OUT} = \Delta E$

$\Delta E = W_{turbine} - W_{pump} + Q_{cond} - Q_{heat\ exchanger}$

$= 44.1hp - 12.88hp + 103.77hp - 129hp \quad = 5.99hp$

(An imbalance has occurred in conservation of energy, this is because the reading of properties of hydrogen is not accurate once it gets closer to absolute zero.

However the earlier assumption of 0% error for properties of hydrogen at all temperature has applied. So we assume that 5.99 ≈ 0)

Thermal Equations:

Main Cycle:

State (5-6):	$W_{in} = m^{\cdot}*(h_6-h_5)$	= 326.30 - 211.90	= 114.4hp
State (6-7):	$Q_{IN} = m^{\cdot}*(h_7-h_6)$	= 1027.00 - 326.30	= 700.7hp
State (7-8):	$W_{out} = m^{\cdot}*(h_7-h_8)$	= 1027.00 - 723.00	= 304.0hp
State (8-5):	$Q_{Loss} = m*(h_8-h_5)$	= 723.00 - 211.90	= 511.1hp

Sub Cycle:

State (1-2):	$W_{in} = m^{\cdot}*(h_6-h_5)$	= 92.81 - 79.93	= 12.88hp
State (2-3):	$Q_{Gain} = m^{\cdot}*(h_3-h_2)$	= 221.80 - 92.81	= 129.0hp
State (3-4):	$W_{out} = m^{\cdot}*(h_3-h_4)$	= 221.80 - 177.70	= 44.1 hp
State (4-1):	$Q_{cond}= m^{\cdot}*(h_4-h_1)$	= 177.7 - 73.93	=103.77hp

Energy Balance:

$W_{T1}+W_{T2}-W_{P1}-W_{P2}-Q_{cond}$= 304+174.64-144.4-51-410.93

= **-97.69hp**

Hydrogen consumption = 0 (fully utilized)

Table 2 Hydrogen Property Table for Model 1

Stage	P (psi)	T (°F)	ρ (lbm/ft³)	h (Btu/lbm)	s (Btu/lbm °R)	State
1	250	-390	1.325	73.93	4.936	Liquid
2	450	-380	1.706	92.81	4.912	Liquid
3	450	-350	0.867	221.80	6.307	Gas
4	250	-371	0.588	177.70	6.293	Gas
5	550	-350	1.080	211.90	6.060	Liquid
6	1500	-306	1.774	326.30	5.997	Liquid
7	1500	-130	0.792	1027.00	9.013	Gas
8	550	-206	0.398	723.00	9.000	Gas

T-S diagram:

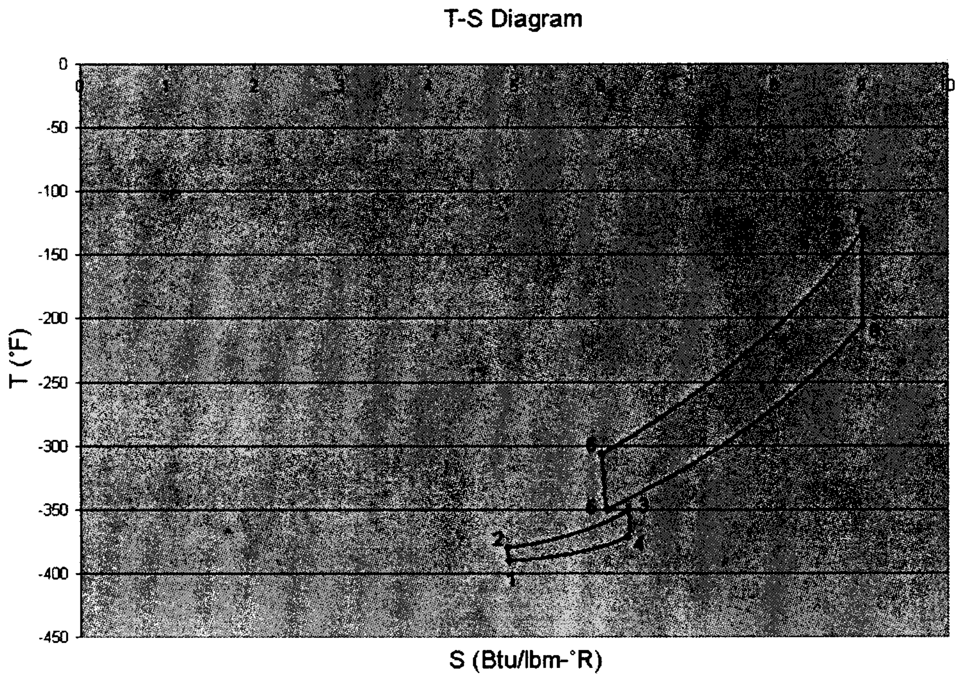


Figure 10 T-S Diagram of the Model1

2.5.5. Thermodynamic Equations for Model 2

Conservation of energy:

There will be no conservation of energy law stands for this condition since the hydrogen used will be disposed.

Thermodynamic Equation:

Main Cycle

- State (5-6): Work input through the pump
  - $W_{in} = m^*(h_6-h_5)$
- State (6-7): Heat gain from outside air
  - $Q_{IN} = m^*(h_7-h_6)$
- State (7-8): Work output of turbine
  - $W_{out} = m^*(h_7-h_8)$
- State (8-5): Heat Loss Due to heat exchange
  - $Q_{Loss} = m^*(h_8-h_5)$

Sub Cycle

- State (2-3): Heat gain from the sub-cycle at Heat exchanger:
  - $Q_{Gain} = m'^*(h_3-h_2)$
- State (3-4): Work output of turbine:
  - $W_{out} = m'^*(h_3-h_4)$

2.5.6. Evaluation of the Model 2 (Working Model)

Description:

After realizing that the ideal model would not work, removing the condenser and the pump in the sub cycle to minimize the energy loss, and not to recycle the hydrogen to reduce the amount of required energy for operation.

Schematics of the Model 2:

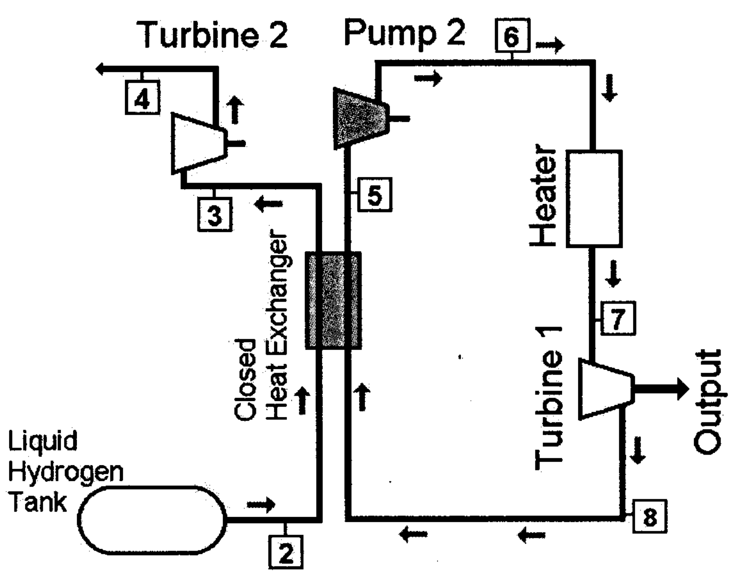


Figure 11 Schematics of Model 2

Calculations:

Thermal Equations:

Main Cycle:

State (5-6):	$W_{in} = m^{\cdot}*(h_6-h_5)$	$= 326.30 - 211.90$	$= 114.4$hp
State (6-7):	$Q_{IN} = m^{\cdot}*(h_7-h_6)$	$= 1027.00 - 326.30$	$= 700.7$hp
State (7-8):	$W_{out} = m^{\cdot}*(h_7-h_8)$	$= 1027.00 - 723.00$	$= 304.0$hp
State (8-5):	$Q_{Loss} = m*(h_8-h_5)$	$= 723.00 - 211.90$	$= 511.1$hp

Sub Cycle:

State (2-3):	$Q_{Gain} = m^{\cdot}*(h_3-h_2)$	$= 221.80 - 92.81$	$= 129.0$hp
State (3-4):	$W_{out} = m^{\cdot}*(h_3-h_4)$	$= 221.80 - 177.70$	$= 44.1$ hp

Energy Balance

$W_{T1}+W_{T2}-W_{P1}= 304+174.64-114.4$

$= \mathbf{364.24hp}$

Hydrogen consumption = (1000/364.24)*4*3600= **39534.37lb/h**

Table 3 Hydrogen Property Table of Model 2

Stage	P (psi)	T (°F)	ρ (lbm/ft^3)	h (Btu/lbm)	s (Btu/lbm °R)	State
2	450	-380	1.706	92.81	4.912	Liquid
3	450	-350	0.867	221.80	6.307	Gas
4	250	-371	0.588	177.70	6.293	Gas
5	550	-350	1.080	211.90	6.060	Liquid
6	1500	-306	1.774	326.30	5.997	Liquid
7	1500	-130	0.792	1027.00	9.013	Gas
8	550	-206	0.398	723.00	9.000	Gas

T-S diagram:

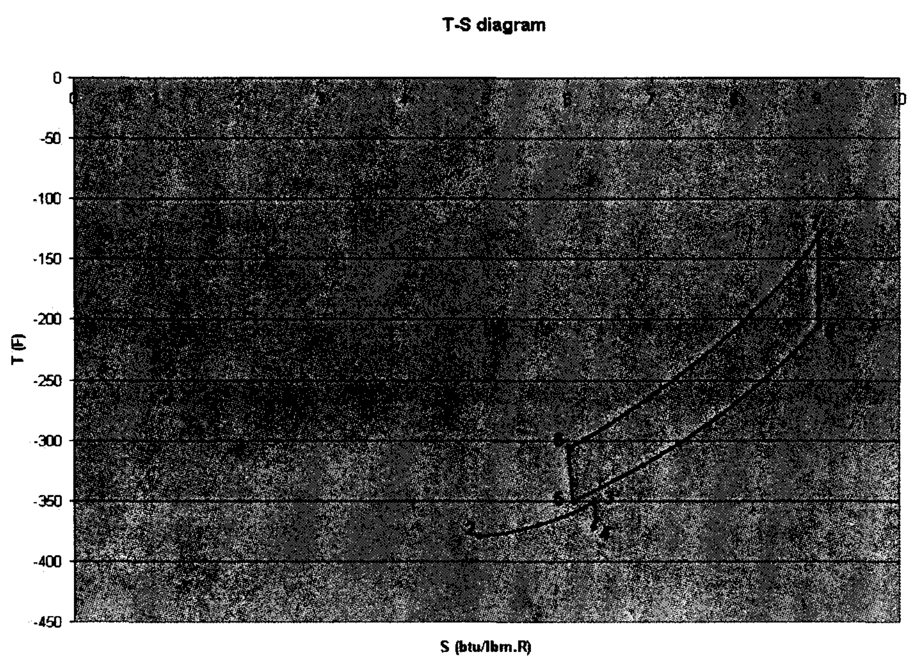


Figure 12 T-S Diagram of the Model 2

2.5.7. Estimation on the Fuel Tank

Known:

- Hydrogen Properties:
  - P_{max} = 10,000psi
  - Density = 5.8lbm/ft^3 @10,000psi, and -390°R (70°F)
- King Air 350 Performance:
  - Cruise Speed = 300mph
  - Optimum Endurance = 5 hours
  - Maximum Fuel Onboard = 3611lb
- Engine Specification
  - Approximate consumption rate = 40,000lb/hr

Case #1

Condition:

- Without any modification, the assigned weight for the maximum fuel onboard is 3,611lb.

Assumption:

- Ignore the size of tank
- Ignore the additional weight due modification
- Ignore the additional weight on the hydrogen turbine engine

Since the maximum fuel onboard is 3,611lb, and the fuel consumption rate is 40,000lb/hr,

3,611 / 40,000 = 0.090 hour = 5.41 minutes (for one engine operation)
= **2.71 minutes (for two engine operation)**

Case #2

Condition:

- Considering a five hour flight endurance

Assumption:

- The size of tank will not affect any aerodynamic characteristics
- Ignore the additional weight due to the modifications and hydrogen
- The weight difference between hydrogen turbine and conventional turbine is negligible.

The fuel required can be determined that (40,000lb/hr * 5 hours) = **200,000lb** (per engine), and assume that the diameter of the tank is about 20ft. By considering the density of the hydrogen at storage condition is 5.8 lbm/ft^3, a volume of **1,160,000 ft^3** is required. From this condition, a total length of 222 ft is required. Which is about a size of Boeing 777 airliner for the size of small plane.

2.5.8. Estimation on the Heat Exchanger 1

One of the heat exchanger tried uses the airplane's wing skin as the heat exchanger. The energy will be transfer through the surface of the wing. This concept allows minimum modifications on the outside shape of the aircraft, so the aerodynamic characteristics of the aircraft will not be changed.

Known:

- The temperature changes from -306°F (154°R) to –130° F (330°R) so the temperature difference = 242°R(°F)
- Area of the heater per engine (1/2) of the total area of the wings = ($303ft^2$ / 2) = $151.5ft^2$
- Ambient Temperature at certain altitudes are:
  - Sea Level   518°R   58°F
  - 10,000ft   483°R   23°F
  - 20,000ft   447°R   -13°F
  - 30,000ft   411°R   -49°F
- From the graph shown below, the convection coefficient (@ 1atm, M=0.86)
  h_{avg} = $600 w/m^2$-K = 105 Btu/hr-ft^2-°F

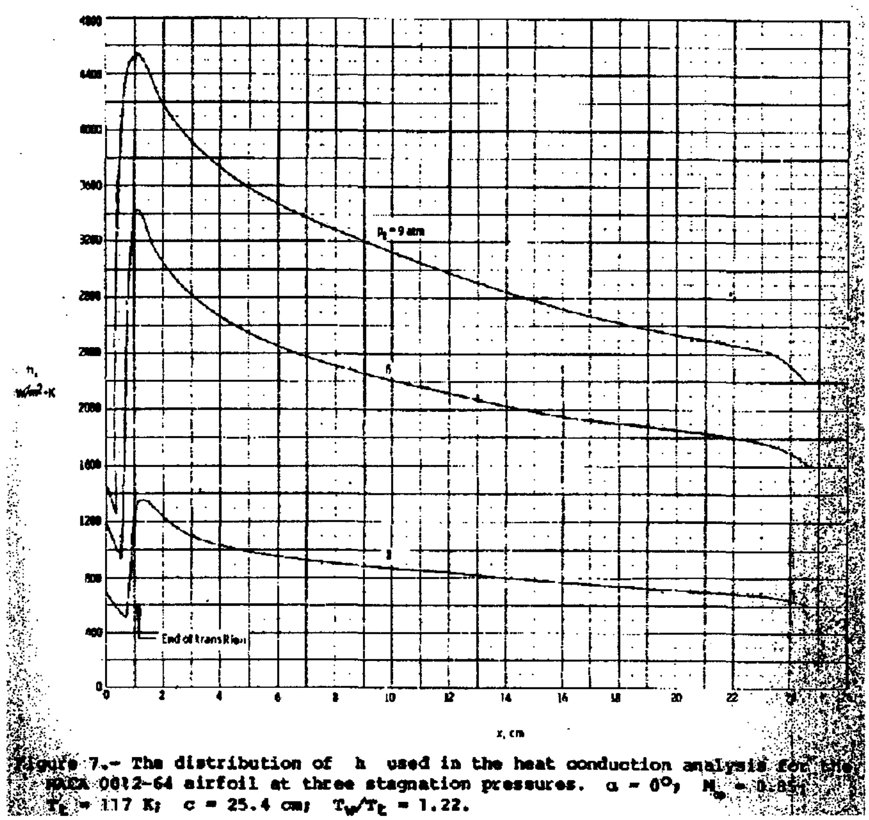


Figure 13 Enthalpy of the stainless steel wing model

Assumption:

The air volume and convection coefficient is directly proportional to each other.

Cruising at Mach 0.4, has the ½ of the value of at Mach 0.8
So, $h = 50$ Btu/hr-ft^2-°F

Energy (sea level) = 813hp (116%)
Energy (30,000ft) = 498hp (71%) can be 100% if area = 210ft^2

2.5.9. Estimation on the Heat Exchanger 2

Liquid –to-Gas Heat Exchangers:

This system will be installed between upper surface and lower surface of the wing. The air will be directory taken at the leading edge of the wing, and no stagnation pressure due to the heating core is assumed. Thus, while the aircraft is flying at 300mph, the velocity of flow is also at the same speed. The opening of the wing is about 1 ft in height, 30 ft long and has about 6 ft in length.

Design specifications of airplane wing heat exchanger:

Table 4 Heat Exchanger 2 (Specifications)

Heat Load, Btu/hr, hp	6,901,194.3; 2,712 hp
Hydrogen temperature in, °F	-306
Hydrogen temperature out, °F	-130
Air temperature in, °F	-93
Air temperature out, °F	-120
Air temperature drop, °F	-27
Air density, lb/ft^3	0.0864
Core matrix	Staggered flat tube-plain plate fin) (Surface number 9.1-0.737-S)
Fin Spacing, fins/in	9.1
Tube size, in	0.737*0.100
Fine material	Copper
Surface area, ft^2/ft^3 (air side)	0.004
Fin area/total area (air side)	224
Free Flow area/frontal area	0.813
Air flow passage hydraulic radius, ft 0.00345	0.788

Equations:

Approximate the area of the pipe to rectangle

Area = w*L From Fig 11.4

= 0.1*0.737

= 0.0737 in^2 = 5.1181e-004 ft^2

D = $(4/\pi*5.1181e\text{-}004)^{1/2}$

= 0.00345 in

V = 300 mph = 440 ft/s

$R_e = VD\rho/\mu$

= (440* 0.00345*0.0864)/(0.0415/3600)

= 10343

$G = R_e * \mu/(4*R_h)$

= 10343*0.0415/(4*0.00345)

= 31104 lb/(hr.ft^2)

$(h/Gc_p)(\mu c_p/k)^{2/3}$ = 0.0038 (Fig. 11.7)

$\mu c_p/k$ = 0.711 Table H2-4

h = (0.0038)(31104)(0.24)($0.711^{0.67}$) = 22.6 Btu/(hr.ft^2.°F)

Fin efficiency is 100%

Surface area, ft^2 = 224 ft^2/ft^3 Figure 11.3

This part requires some iteration:

Assume temperature of the air leaving the wing leaving the wing is –120 °F

Table 5 Heat Exchanger 2 (Temperature)

Tc_{in}, °F	Tc_{out}, °F	Th_{in}, °F	Th_{out}, °F	GTD, °F	LTD, °F	$LMTD_c$	$LMTD_R$
-305	-130	-93	-120	-212	-10	-66.1	-65
-305	-130	-93	-115	-212	-15	-74.3	-80
-305	-130	-93					
-305	-130	-93					
-305	-130	-93					

LMTD = $[(Tc_{in} - Th_{out})-(Tc_{out}- Th_{in})]/\ln[(Tc_{in} - Th_{out})-(Tc_{out}- Th_{in})]$

= (-306+120) – (-130+93)/ln[(-306+120)/(-130+93)]

LMTDc = -66.1 °F

$LMTD_R$ = -65 °F (Fig.11-7)

Heat Transfer of inlet face area = $hA\Delta T$

= (22.6)(112)(65) = 164530 Btu/(hr.ft)

Inlet face area required = 6901194.3 /164530 = 42 ft^2

Assume the length of the heat exchanger is 21 ft

Fin spacing is 9.1 per inch.

For a length of 21 ft length of the heat exchanger there will be 2293.2 in fin spacing

2.6. *Final Design Analysis:*

Description:

The final design of the system is made under assumptions described here.

- The hydrogen can be existed only in liquid form, or in gas form. (In order to avoid complication of the analysis.)
- The values from the sources are assumed to be correct, or the errors are less than that requires additional considerations.

The final design consists of the combination of three Model 1 and a Model 2, the mass flow rate is 4 time larger than the original.

Equations:

Conservation of energy

$E_{IN} - E_{OUT} = \Delta E$

$\Delta E = W_{turbine} + Q_{heat\ exchanger} - Q_{heat\ sources} - W_{pump} = 0hp$

Main Cycle

- State (5-6): Work input through the pump
  - $Win = m^*(h_6 - h_5)$
- State (6-7): Heat gain from outside air
  - $Q_{IN} = m^*(h_7 - h_6)$
- State (7-8): Work output of turbine
  - $Wout = m^*(h_7 - h_8)$
- State (8-5): Heat Loss Due to heat exchange
  - $Q_{Loss} = m^*(h_8 - h_5)$

Sub Cycle

- State (1-2): Work input through the pump
  - $Win = m^*(h_6 - h_5)$
- State (2-3): Heat gain from the sub-cycle at Heat exchanger:
  - $Q_{Gain} = m'^*(h_3 - h_2)$
- State (3-4): Work output of turbine:
  - $Wout = m'^*(h_3 - h_4)$
- State (4-1): Energy needed for condenser:
  - $Q_{cond} = m'^*(h_4 - h_1)$

Schematics of the Final Model:

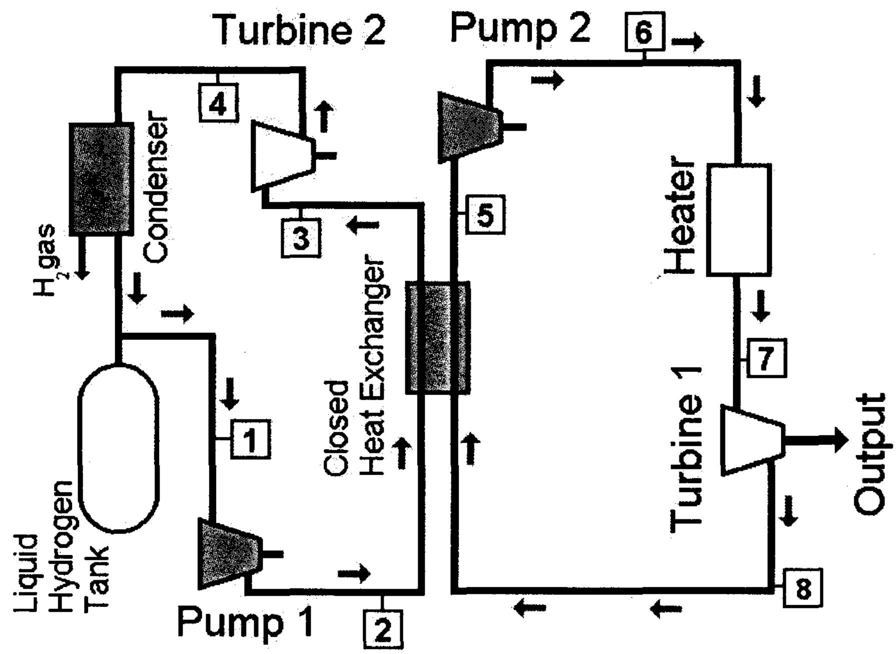


Figure 14 Schematics of the Final Model

Table 6 Final Model

Stage	P (psi)	T (°F)	ρ (lbm/ft³)	h (Btu/lbm)	s (Btu/lbm °R)	State
1	250	-390	1.325	73.93	4.936	Liquid
2	450	-380	1.706	92.81	4.912	Liquid
3	450	-350	0.867	221.80	6.307	Gas
4	250	-371	0.588	177.70	6.293	Gas
5	550	-350	1.080	211.90	6.060	Liquid
6	1500	-306	1.774	326.30	5.997	Liquid
7	1500	-130	0.792	1027.00	9.013	Gas
8	550	-206	0.398	723.00	9.000	Gas

T-S Diagram:

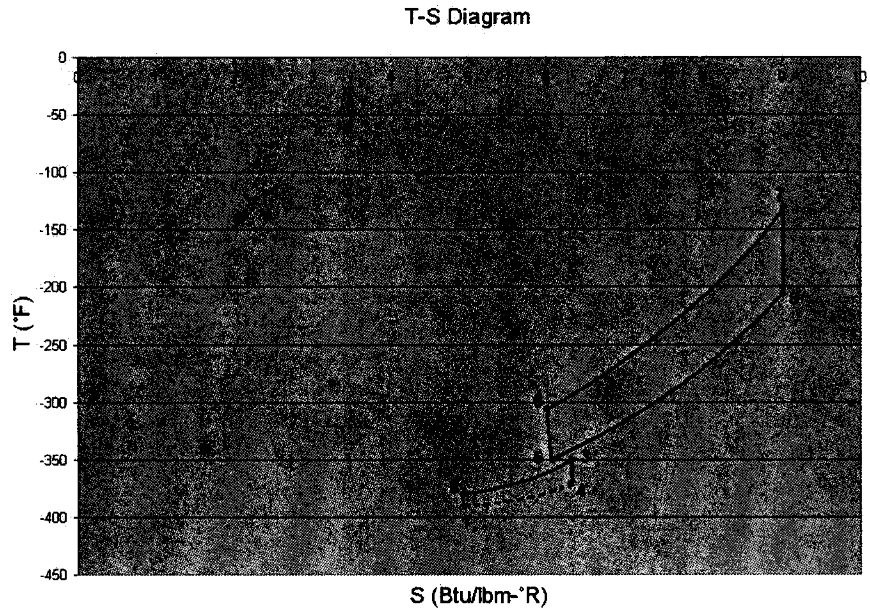


Figure 15 T-S Diagram of the Final Model

3. Conclusions and Recommendations

These are the conclusions of the calculations from the model 1, 2 and the final models.

Find the mass flow difference between both closed system

Assume $m_1=1$
State (8-5)
$Q_{loss} = m^{\cdot}_1 *(h_8-h_5)$
$= 1*(723-211.9)$
$= 511.1hp$

Assume Q_{gain} in sub-system equal to Q_{loss} in main system
State (2-3)
$Q_{gain}=m^{\cdot}_2 *(h_3-h_2)$
$m^{\cdot}_2= 511.1/(221.8-92.81)$
$= 3.96$

So the ratio of mass flow rate of main system ($m^{\cdot}_1$) to sub-system ($m^{\cdot}_2$) is **1 : 3.96 ≈ 1:4**

Multiply all W_{p2}, W_{T2}, Qc in sub-system by constant of k= 4, 3, 2, 1
For different mass flow rate ratio approach. Then calculate the net Horsepower for these constant

For K= 4 (ideal approach)

$W_{T1}+W_{T2}-W_{P1}-W_{P2}-Q_{cond}= 304+174.64-144.4-51-410.93$
$= -97.69hp$
Hydrogen consumption= 0 (fully utilized)

For K= 1

$W_{T1}+W_{T2}-W_{P1}-W_{P2}-Q_{cond} = 304+174.64-114.4-12.88-103.77$
$= 247.59hp$
Hydrogen consumption= (1000/247.59)*3*3600= 43620.5lb/h

For K=2,3 is intermediate between K=1 and K=4

For K=4 (without condenser and pump2)
* Pump2 not needed when condenser has been taken off
$W_{T1}+W_{T2}-W_{P1}= 304+174.64-114.4$
$= 364.24hp$
Hydrogen consumption= (1000/364.24)*4*3600= 39534.37lb/h

The hydrogen package used to determine the properties has been updating as necessary, so there is no guarantee that the value is always right. In fact, the program was upgraded during the project and it complicated the situation sometimes. For the each model, the conclusions are made as seen below.

1. The original model does not work, or cannot be determined its functionality since the mixed state of the hydrogen compromise the calculation, and functions.
2. Model 1 is the ideal model, which follows the thermodynamic laws perfectly. Although there are no considerations in the efficiency, it requires additional 98 horsepower to make the system balanced.
3. The model 2 does not recover any hydrogen used. This system works, but a large amount of hydrogen loss is in evitable. In fact this system generates about 247 hp, but loses about 43,620lb of hydrogen each hour.
4. The final model loses about 39,500lb of hydrogen each hour to generate 1,000 hp of output. This mode is a combination of model 1 and model 2, so the part of hydrogen will be condensed back into hydrogen tank.
5. Heat exchanger concept 1 is based on 100% efficiency, about 700hp of performance was expected. When the efficiency was applied for both turbine and pump (about 80% for both), the value jumped to 2,700hp so this system cannot provide enough power output required.
6. Heat exchanger concept 2 take the value after the efficiency was taking into account. 2,700hp can be generated but a large temperature difference is required while air is moving at 300mph.
7. The approximation of the tank was very easy to perform since there was particular information available from the NASA's archive. Since the weight of tank is heavier than the one for jet fuel, the consumption of the fuel must be minimized at all cost. 3 minutes of flight is not enough for any kind of flight, and the King Air cannot carry the tank weigh 20,000lb and 200,000lb of fuel.

A few recommendations can be made for this proposal.

1. Since this may be a good way to extract energy while the hydrogen is turning from liquid to gas, it is possible to utilize this system to generate extra energy for hydrogen turbine engines being developed by Boeing or Daimler Aerospace.
2. Burning hydrogen as fuel can provide a vast amount of energy to the system so all the hydrogen turned to gas should be burned in a combustion chamber to acquire energy.
3. Spacecraft in the space has a large temperature differences between the side facing sun and the opposite side. There maybe a possibility to use this large temperature difference to evaporate and condense hydrogen.

4. References / Bibliographies:

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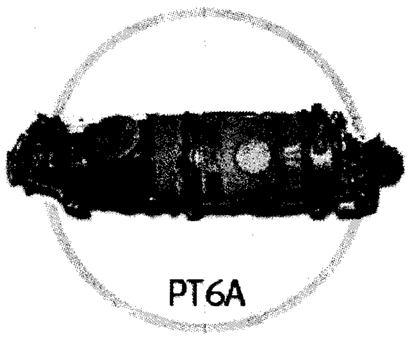
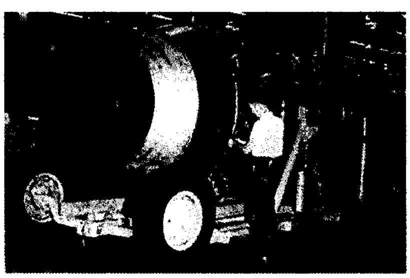
5. Appendix

5.1. Engine Specification: PT6A-60A



Fuel:	Jet-A
Fuel Consumption:	1,000lb/hr
Power Output:	1050SHP
Length:	6ft
Diameter:	1.7ft
Weight:	465lb

5.2. Engine Specification: Model 304



Fuel:	Hydrogen
Fuel Consumption:	12,500lb/hr
Power Output:	12,000HP
Length:	34ft
Diameter:	6.6ft
Weight:	6,000lb

5.3. *Reference: Figure 11.8*

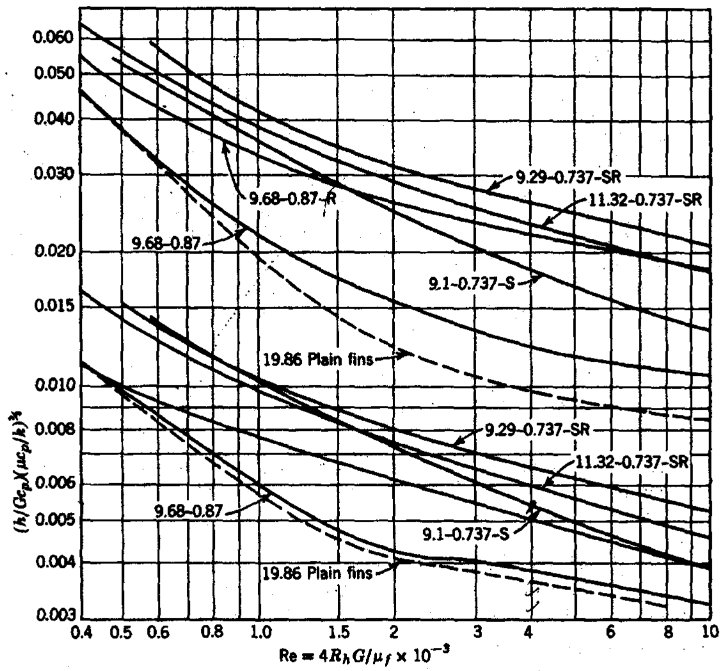


Figure 11.7 Curves for the Colburn modulus and friction factor as functions of the Reynolds number for the flattened tube-plate fin surfaces of Fig. 11.3. (Kays and London, Ref. 5.)

p. 178

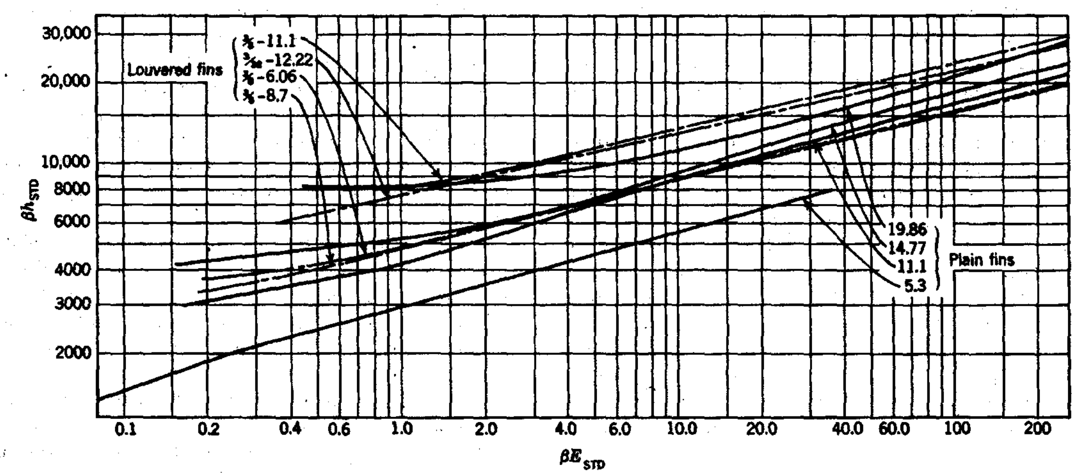


Figure 11.8 Amount of heat transferred per cubic foot of heat-transfer matrix as a function of the pumping power required for the plain plate-fin matrices of Fig. 11.3. The symbol h_{STD} is the heat-transfer coefficient for an arbitrary set of conditions taken as standard for the test. (Kays and London, Ref. 5.)

181

Figure 16 Figure 11.7 and 11.8

5.4. *Reference: Figure 11.3*

Figure 11.3 *(continued)*

Summary of Geometric Parameters

Surface Designation	Fins per in.	Hydraulic Radius, R_h, ft	Plate Spacing, b, in.	Tube or Fin Thickness, in.	Extended Surface Area per Unit of Total Area, ft²/ft²	Gas-Side Surface Area per Unit Volume Between Plates, ft²/ft³	Gas-Side Surface Area per Unit Volume of Matrix, α, ft²/ft³	Free Flow Area per Unit of Inlet Face Area, ft²/ft²
Plate-fin type:								
Plain fins								
5.3	5.3	0.00504	0.470	0.006	0.719	156		
11.1	11.1	0.00253	0.250	0.006	0.730	334		
14.77	14.77	0.00212	0.330	0.006	0.831	369		
19.86	19.86	0.001495	0.250	0.006	0.833	455		
Louvered fins								
3/8–6.06	6.06	0.00365	0.250	0.006	0.623	239		
3/8–8.7	8.7	0.00299	0.250	0.006	0.687	288		
3/8–11.1	11.1	0.00253	0.250	0.006	0.730	339		
3/32–12.22	12.22	0.002941	0.485	0.004	0.862	302		
Fin-flat-tube type:								
9.68–0.870	9.68	0.00295		0.004	0.795		229	0.697
9.68–0.870-R	9.68	0.00295		0.004	0.795		229	0.697
9.1–0.737-S	9.10	0.00345		0.004	0.813		224	0.788
9.29–0.737-S-R	9.29	0.00338		0.004	0.814		228	0.788
11.32–0.737-S-R	11.32	0.00288		0.004	0.845		270	0.780

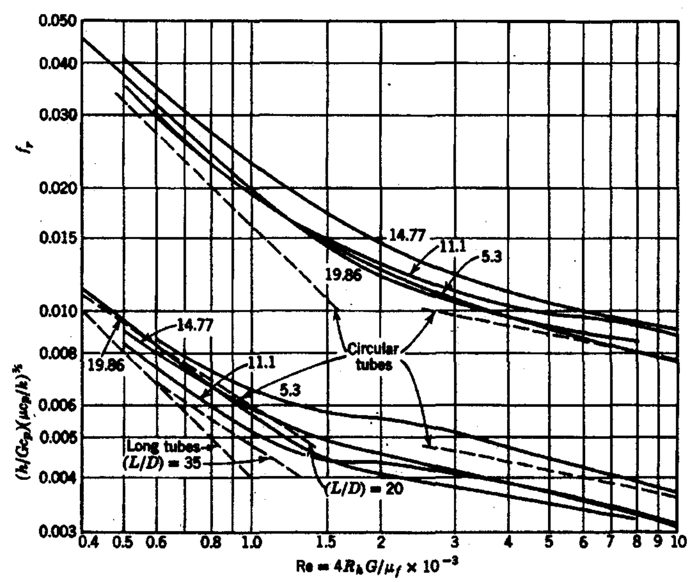


Figure 11.4 Curves for the Colburn modulus and friction factor as functions of Reynolds number for the four plain plate-fin, heat-transfer matrices of Fig. 11.3. (Kays and London, Ref. 5.)

179

Figure 17 Figure 11.3 and 11.4

5.5. *Reference: Table H2.3*

Table 7 Table H2.3

Table H2.3 Heat transfer properties of liquids*

Temperature °F	c_p Btu/lb·°F	k Btu/lb·ft·°F	μ lb/hr·ft	ρ lb/ft³	G'_{Tr} lb/sec·ft²	$\frac{c_p\mu}{k}$	$\left(\frac{c_p\mu}{k}\right)^{0.4}$	$\left(\frac{c_p\mu}{k}\right)^{0.67}$	ϕ_t
Water									
32	1.0293	0.337	4.32	62.54	28.8	13.2	2.80	5.59	0.455
200	1.0039	0.393	0.738	60.2	4.92	1.88	1.287	1.524	1.00
400	1.075	0.382	0.32	53.62	0.976	0.91	0.963	0.939	1.41
600	1.525	0.293	0.215	42.37	0.934	1.08	1.03	1.053	1.705
Aqueous solution 30% ethylene glycol									
60	0.882	0.276	6.04	64.9	40.2	19.6	3.295	7.28	0.3355
100	0.900	0.285	3.27	64.3	21.8	10.3	2.54	4.74	0.436
200	0.934	0.292	1.23	62.1	8.2	3.93	1.73	2.49	0.638
300	0.970	0.285	0.692	59.2	4.61	2.355	1.408	1.77	0.899
Ethylene glycol									
60	0.556	0.169	62.1	69.4	414	204	8.4	34.8	0.0807
100	0.581	0.1595	25.1	68.7	167.3	91.4	6.09	20.3	0.1143
200	0.644	0.135	5.67	66.2	37.8	27.05	3.74	9.04	0.189
300	0.706	0.111	2.295	63.3	15.3	14.6	2.92	5.97	0.259
H_2 (liquid)									
−430	1.91	0.0636	0.0447	4.67	0.298	1.345	1.126	1.218	1.895
−410	4.44	0.0796	0.0204	3.69	0.136	1.135	1.052	1.088	2.92
N_2 (liquid)									
−210	0.500	0.041	0.162	34.5	1.08	1.975	1.313	1.575	0.356
−110	0.474	0.095	0.756	54.0	5.04	3.75	1.696	2.41	0.313
NH_3 (liquid)									
0	1.08	0.29	0.567	42.0	3.71	2.075	1.499	1.96	1.06
100	1.17	0.29	0.172	35.6	1.14	0.694	0.864	0.784	1.585
Dowtherm A									
200	0.432	0.0863	2.71	62.6	18.05	13.56	2.84	5.67	0.1405
400	0.600	0.105	1.14	56.8	7.60	6.51	2.115	3.49	0.295
600	0.700	0.1037	0.727	50.5	4.85	4.90	1.89	2.885	0.393
Methyl alcohol									
0	0.57	0.124	2.80	51.3	18.70	12.87	2.78	5.50	0.237
100	0.615	0.1205	1.15	48.1	7.67	5.87	2.03	3.258	0.338
200	0.65	0.117	0.666	43.1	4.45	3.70	1.687	2.39	0.401
Freon-11									
0	0.198	0.06	1.639	98.27	10.92	5.40	1.96	3.08	0.123
100	0.212	0.053	0.920	90.19	6.14	3.68	1.685	2.38	0.147
200	0.225	0.046	0.637	80.94	4.25	3.12	1.576	2.135	0.151
Freon-114									
0	0.23	0.044	1.452	98.62	9.68	7.58	2.25	3.85	0.1143
100	0.2412	0.0353	0.809	88.37	5.39	5.53	1.982	3.12	0.125
200	0.2627	0.027	0.600	79.0	4.00	5.84	2.02	3.24	0.118
Gasoline									
0	0.447	0.110	2.60	49.7	17.35	10.58	2.57	4.81	0.204
200	0.565	0.103	0.745	42.7	4.97	4.08	1.748	2.55	0.354
400	0.683	0.0967	0.336	36.8	2.24	2.37	1.413	1.78	0.510
Kerosene									
0	0.430	0.101	17.1	52.5	114	72.8	5.55	17.5	0.0897
200	0.545	0.095	1.59	47.4	10.6	9.12	2.42	4.37	0.247
400	0.655	0.0892	0.625	42.4	4.17	4.58	1.839	2.76	0.3705
600	0.745	0.0829	0.31	38.1	2.07	2.78	1.506	1.978	0.494

*Data from Refs. 1–15 were selected, plotted, and averaged to yield the values given here for c_p, k, μ, and ρ.

5.6. Reference: Figure H4.1 LMTD

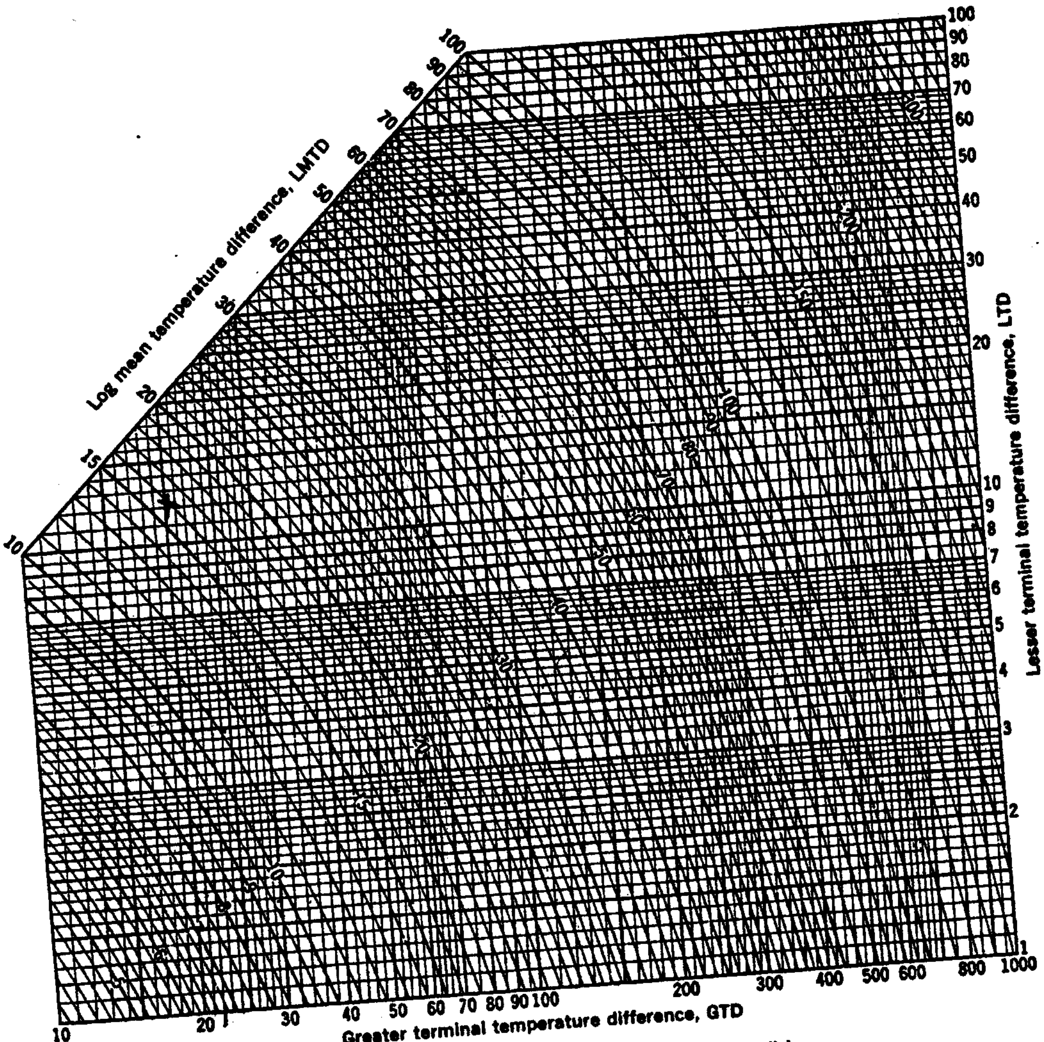


Figure H4.1 LMTD as a function of the terminal temperature differences for pure parallel or counterflow heat exchangers. If a point falls off the chart, multiply the scales by a factor such as 10, and the value then found on the chart by the same factor. (Courtesy Industrial Equipment Division, Baldwin-Lima-Hamilton Corp.)

Figure 18 Figure H4.1 LMTD

5.7. Reference: Figure 11.4