

Thermal Management System for Fiber Lasers using MATLAB

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Abstract— Fiber lasers nowadays are used extensively for various operations because of their exceptional beam quality. Fiber laser, when operated for various applications, generate heat at high power-regimes. To maintain its working by suppressing thermal issues, a cooling circuit must be considered. This paper deals with the design of a chiller circuit on MATLAB to optimize the cooling system which will be used to suppress the heat generation by the laser for its efficient working. Further, it shows how the circuit will be affected when the compressor fails to perform. Using the concepts of heat and mass transfer, the model gives a good picture of the actual behavior of the cooling circuit under different conditions of the laser being operated. This paper shows simulation on MATLAB and the data as well as the graphs obtained from these simulations. The main task for this work is, therefore, to build a computational model to simulate the thermal response of the cooling system of a laser being operated under different conditions.

Keywords: Fiber Laser; Chiller Circuit; Refrigerant; Operating Temperature; Pressure Drop; MATLAB;

1 Introduction

Fiber Lasers have gained a lot of attention over the past few years. Due to better compactness, dynamic heat generation and exceptional spatial beam quality, fiber lasers are now used in various scientific and industrial applications. To make sure the laser maintains its beam quality, the heat generated by them must be removed. Most of the heat converted from the optical power takes place in the fiber core, where most of the pump power is absorbed. To maintain the working temperature of the laser, a chiller circuit is designed. It is worth noting that, whilst the fiber laser is resistant to thermal effects to a large extent at low powers, there are significant characteristics and restrictions in a kilowatt power domain which influence laser performance and cannot be ignored. In one embodiment, pump-induced heating can cause several serious problems, comprising;

- Formation of thermal cracks due to internal thermal stress and expansion
- Shortening of fiber lifetime owing to damage of fiber coatings
- Degrading of laser beam quality due to thermal lensing
- Deterioration of optical coupling efficiency affected by the undesirable temperature-induced motion of mechanical parts
- Enhancement of mode instability and mode distortion
- Reduction of laser quantum efficiency and gain coefficient
- Intensification of threshold power [1]

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1.1 The Chiller Circuit

A Chiller circuit was designed on MATLAB that removes heat from a liquid via a refrigeration cycle. This liquid was then circulated through a plate-type heat exchanger.

The Chiller circuit for the system comprises of the following:

- Refrigeration System
- Two Tanks
- Three Pumps
- Spillover
- Evacuation System

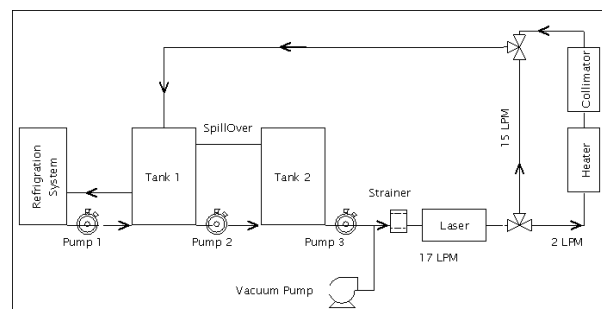


Fig. 1. Circuit Schematic

The schematic shows the circuit which ensures smooth running of laser. Since the laser has a heat load of 4.1kW and has an operating temperature at 19 to 21 degree Celsius, so a continuous cooling circuit was required which gives the designers liberty to give their input parameters. Using the model, the designer can vary the flowrates of different fluids in the circuit, heat load of all the components, vary the volume of the tanks and can see different results to ensure the operation of all the components.

The system comprises of a refrigeration cycle with R407c as the refrigerant. The refrigeration cycle is given a target temperature which brings down the temperature of the refrigerant to -5 degree Celsius. The system comprises of two tanks named as Tank 1 and Tank 2 filled with water. Volume of Tank 1 is taken to be 30 liters. Initially both the tanks are at normal atmospheric temperature and pressure. Tank 1 is maintained at 5 degree Celsius by introducing an electric pump which connects the refrigeration cycle and Tank 1 through a plate type heat exchanger. This pump will stop working when the temperature of the tank is in-between 4-6 degree Celsius.

In a plate type heat exchanger, the heat transfer surface consists of a number of thin corrugated plates pressed out of a high-grade metal. The prime reason to use PHE is that there is no direct contact of the fluids which reduces water contamination.

Volume of Tank 2 is taken to be 50 liters. Water from Tank 1 will be pumped to Tank 2 which will maintain the temperature of 21 degree Celsius using an electric pump which will stop working when the temperature is in the range of 20-22 degree Celsius.

From Tank 2, water is pumped using another pump to the laser heat source. There's a three-way valve that divides the flowrate since the collimator and the heater runs at different flowrates. The reason of using a heater after the laser is to increase the temperature of the fluid as the minimum working temperature of the collimator is 30-33 degree Celsius. So, the heater ensures a 5 degree rise in the temperature.

For volume balancing between the two tanks, a Spillover is introduced which is installed at the top of the tanks.

The pressure drop across all the components was calculated to ensure sufficient head, and flowrate is provided by the pump to all the components in the circuit.

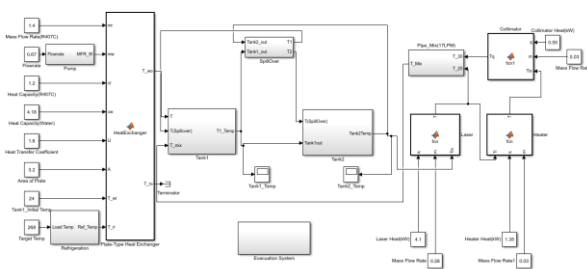


Fig. 2. Chiller Circuit on MATLAB

2 Background Theory

2.1 Refrigeration Cycle

The main function of a refrigeration cycle is to maintain the temperature of the heat source below that of its surroundings while transferring the extracted heat, and any required energy input, to a heat sink, atmospheric air or surface water.

Different processes involved:

- Evaporation
- Superheating
- Compression
- Condensation
- Throttling and expansion

All the mentioned processes were implemented on MATLAB and the refrigerant was given a target temperature of -5 degree Celsius. Designer has the choice of choosing the refrigerant for the circuit. Data of R407c was given and model was simulated as shown in figure 3.

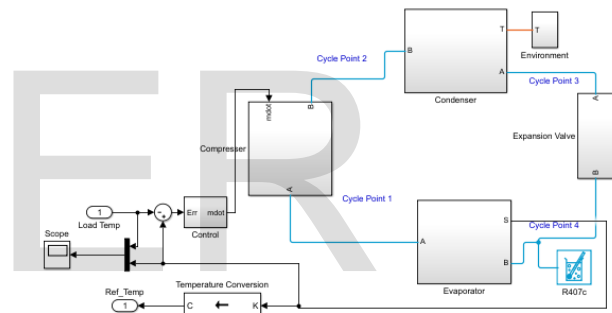


Fig. 3. Refrigeration Cycle with R407c as the refrigerant

2.2 Heat Exchanger

LMTD method is useful for determining the size of a heat exchanger to calculate the outlet temperature when the mass flow rates and the inlet and outlet temperatures of the hot and cold fluids are given. Another issue is the determination of the heat transfer rate and the outlet temperatures of the hot and cold fluids for prescribed fluid mass flow rates and inlet temperatures when the type and size of the heat exchanger are specified. When all the inlet and outlet temperatures are specified, the size of the heat exchanger can easily be determined. But the outlet temperature is not known. The LMTD method could still be used for this alternative problem, but the procedure would require tedious iterations, and thus it is not practical. In an attempt to eliminate the iterations from the solution of such problems, Kays and London came up with a method in 1955 called the ϵ -NTU method, which greatly simplified heat exchanger analysis.

$$\epsilon = \frac{Q}{Q_{max}}$$

$$Q = C_c (T_{c,out} - T_{c,in}) = C_h (T_{h,in} - T_{h,out})$$

The heat transfer in a heat exchanger will reach its maximum value when:

- The cold fluid is heated to the inlet temperature of the hot fluid
- The hot fluid is cooled to the inlet temperature of the cold fluid

These two limiting conditions will not reach simultaneously unless the heat capacity rates of the hot and cold fluids are identical (i.e. $C_c = C_h$). When $C_c \neq C_h$, which is usually the case, the fluid with the smaller heat capacity rate will experience a larger temperature change, and thus it will be the first to experience the maximum temperature, at which point the heat transfer will come to a halt. The temperature rise of the cold fluid in a heat exchanger will be equal to the temperature drop of the hot fluid when the mass flow rates and the specific heats of the hot and cold fluids are identical. Since the Plate Heat Exchanger sourced is counter flow, the formula for effectiveness will be

$$\epsilon = \frac{(1 - e^{-NTU(1-Cr)})}{(1 - Cr * e^{-NTU(1-Cr)})}$$

NTU method was implemented using this concept for Plate Type Heat Exchanger to calculate the temperature of water after heat exchange with the refrigerant in MATLAB.

2.3 Different refrigerants and their comparison

A Refrigerant is the primary working fluid used for absorbing and transmitting heat in a refrigeration system. Refrigerants absorb heat at a low temperature and low pressure and release heat at a higher temperature and pressure.

To compare the relative ozone depletion caused by various refrigerants, an index called the ozone depletion potential (ODP) has been proposed. ODP is the ratio of the rate of ozone depletion of 1 lb. of any halocarbon to that of 1 pound of CFC-11. The ODP of CFC-11 is assigned a value of 1. Similar to the ODP, the halocarbon global warming potential (HGWP) or simply GWP is the ratio of calculated warming for each unit mass of gas emitted to the calculated warming for a unit mass of reference gas CFC-11. With R-134a also in the list of refrigerants which will phase out soon so an alternate refrigerant having low ODP and properties similar to that of R-134a should be used.

Comparing the GWP of all the refrigerants listed in the table below, HFO-1234yf has GWP less than 1. But it is not easily available. Similarly, R-152a comes next with low GWP but the compressors available for this refrigerant are not available since this refrigerant has recently been approved. So, R-407c was selected as the refrigerant because it is a replacement for R-134a and can retrofit its equipment. [4]

Table 1. Comparison of different refrigerants

| Properties | R134a | R152a | R407c | HFO-1234yf |
|--------------------------|----------------------|---|---|------------------------|
| Composition | 100%, CF3C H2F | 100%, CHF2C H3 | R32a (23%) R125a (25%) R134a (52%) | 100%, CH2=CF CF3 |
| Molecular Weight | 102.3 | 66.1 | 86.2 | 114 |
| Boiling Point (1atm, C) | -26.06 | -25 | -42 | -30 |
| Critical Pressure (psia) | 588.3 | 651.51 | 672.61 | |
| Critical temperature (C) | 101 | 113.5 | 86.1 | 94.7 |
| ODP | 0 | 0 | 0 | 0 |
| GWP | 1430 | 140 | 1770 | Less than 1 |
| Replacement for | R12, R22, R123 | R134a | R22, R134a | R134a |
| Availability | Easily Available | It has recently been approved for use in automobile applications. | Can retrofit R22 and R134a equipment. | Not easily available |

2.4 Pressure drop calculations

Higher the viscosity of the liquid, higher the resistance to flow, therefore, higher the friction loss. To check whether the fluid is turbulent or laminar, the value of Reynolds number is calculated which quantifies the relative importance of viscous and inertial forces for a given fluid condition.

$$Re = \frac{\rho uL}{\mu} = \frac{uL}{\nu}$$

Table 2. Pressure drop across major components

| Component | Approximate Pressure Drop (bar) |
|------------|---------------------------------|
| Laser | 2.5 |
| Collimator | 0.2 |
| Strainer | 0.4 |

There are different factors that significantly affect the head loss. These include:

- Flowrate of the fluid
- Inside diameter of the pipe
- Roughness of the pipe wall
- Corrosion and scale deposit
- Viscosity of the fluid
- Length of pipe
- Fittings such as elbows, tees, valves, etc.
- Straightness of pipe

To predict the head loss in pipes and fittings, the formula called the Darcy Weishbach was used.

$$H_L = \frac{fL(V^2)}{2Dg}$$

Where 'f' is the friction factor related to the roughness of the pipe.

But to calculate the friction factor, the phenomenological Colebrook-White equation which expresses the Darcy friction factor as a function of Reynolds number Re and pipe relative roughness ϵ / D_h , fitting the data of experimental studies of turbulent flow in smooth and rough pipes. For a conduit flowing completely full of fluid at $Re > 4000$, it is expressed as

$$\frac{1}{\sqrt{f}} = \frac{-2 \log\left(\frac{\epsilon}{3.7Dh} + \frac{2.51}{Re\sqrt{f}}\right)}{1}$$

Also, as an approximation of the implicit Colebrook-White equation, Sawmee-Jain equation was used to compare the frictional factor obtained using Colebrook-White function.

$$\frac{1}{\sqrt{f}} = \frac{-2 \log\left(\frac{\epsilon/D}{3.7} + \frac{5.74}{Re^{0.9}}\right)}{1}$$

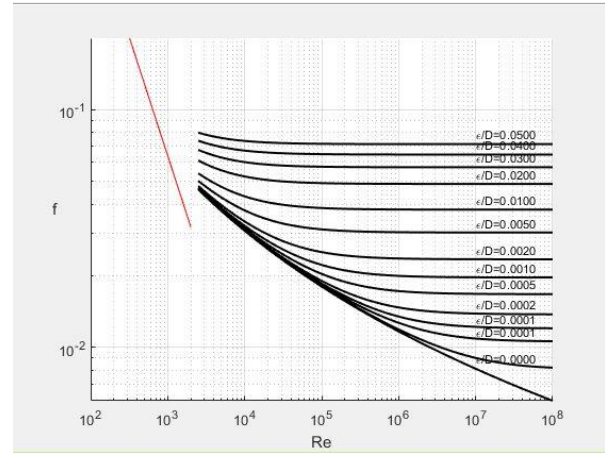


Fig. 4. Moody Chart on MATLAB

Using these concepts, the pressure drop across all the lines was calculated on MATLAB. The pressure drop obtained: 4.005 bar.

3 Back Up System

The core of a refrigeration system is the compressor that is designed to pump cool refrigerant from the evaporator into the condenser.

Refrigeration compressors need to be properly maintained and require periodic inspection and testing. Unfortunately, the compressor is often ignored until it malfunctions or stops running. Under such circumstances we have to check for how long we can operate the laser. Since the temperature of the water at the inlet of the laser should not exceed 25 degree Celsius so we have to calculate the time at which the temperature of Tank 2 reaches 25 degree Celsius when the refrigeration circuit is not working. Also, the power input to the heater will reduce since due to the absence of refrigeration circuit, the temperature of both the tanks will eventually rise so there is no need to provide a constant heat load. So, a variable heat load was given which reduces the power consumption from the generator.

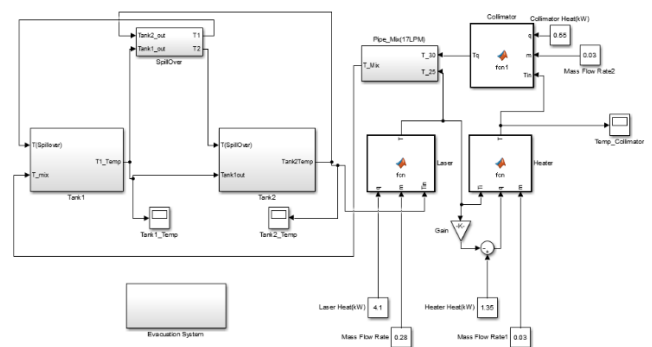


Fig. 5. Back Up System on MATLAB

4 Results Obtained

MATLAB model was simulated and results were obtained for the following components:

Table 3. Components with their heat load

| Component | Heat generation (kW) |
|------------|----------------------|
| Laser | 4.1 |
| Heater | 1.35 |
| Collimator | 0.55 |

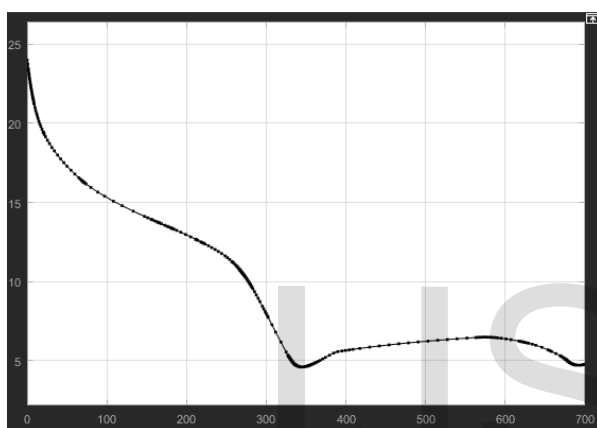


Fig. 5. Temperature of Tank 1 with time

From Figure 5, the temperature drops to 5 degree Celsius in 350 seconds.

Table 4. Time to reach 21 degrees Celsius in Tank 2 at different flow rates

| Flow rate of Pump 2 (LPM) | Time to reach 21 degree Celsius in Tank 2 (s) |
|---------------------------|---|
| 10 | 258 |
| 12 | 243 |
| 14 | 233 |
| 15 | 223 |

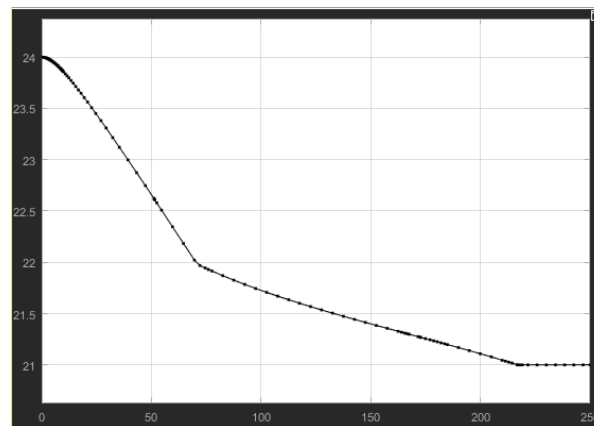


Fig. 6. Temperature of Tank 2 with time

Figure 6 is for 15 LPM flowrate of pump 2 which brings down the temperature of tank to 21 degree Celsius in 223 seconds.

Figure 7 shows the variation of temperature in Tank 2 when pump 2 operates at 10 LPM. The nature of the graph was expected like this. The graph shows how the temperature in Tank 2 first decreases due to the water pumped from Tank 1 then after some time the temperature starts rising.

The temperature of Tank 2 reaches 25 degree Celsius in 765 seconds i.e. 12.75 minutes as seen from figure 7. This means that the laser can be operated for 12.75 minutes if the compressor stops working.

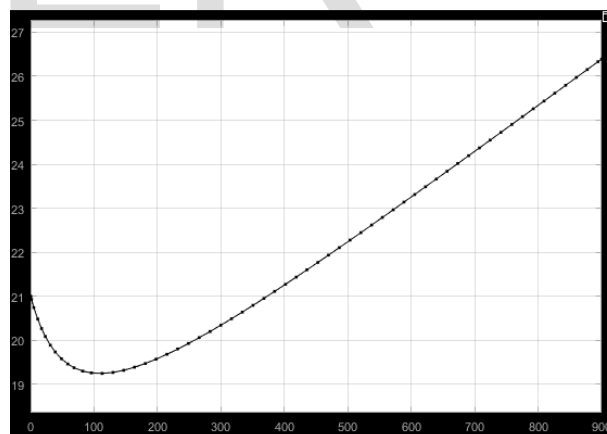


Fig. 7. Temperature of Tank 2 to reach 25 degree Celsius

Table 5. Time to reach 25 degrees Celsius of Tank 2 at different flow rates

| Flow rate of Pump 2 (LPM) | Time to reach 25 degree Celsius of Tank 2 (s) |
|---------------------------|---|
| 10 | 765 |
| 12 | 728 |
| 14 | 698 |
| 15 | 679 |

Table 5 shows how the backup time can be varied by varying the flowrate.

5 Conclusion

The model build gives a good picture of the chiller circuit for cooling a laser in operation. The conclusion from the pressure calculations can be useful for the designer during selection of the pump. Instead of changing the components, the designer can vary different parameters of those components and can optimize the circuit and hence reducing testing time. The model built during this work is an example of what is possible to do and simulate in MATLAB. This model can therefore be a starting point for further modelling because of its accurateness for volume flow rate, pressure drop, and thermal aspect.

6 References

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