UAEU College of Engineering

جامعة الإمارات العربية المتحدة
United Arab Emirates University

United Arab Emirates University
College of Engineering
Graduation Project II Course

Designing and building a cooling system with enhanced heat transfer features based on novel ideas utilizing heat transfer cooling media

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- Performance evaluation
- Environmental analysis and discussion
- New skills learnt and Way forward

Problem Statement and Purpose

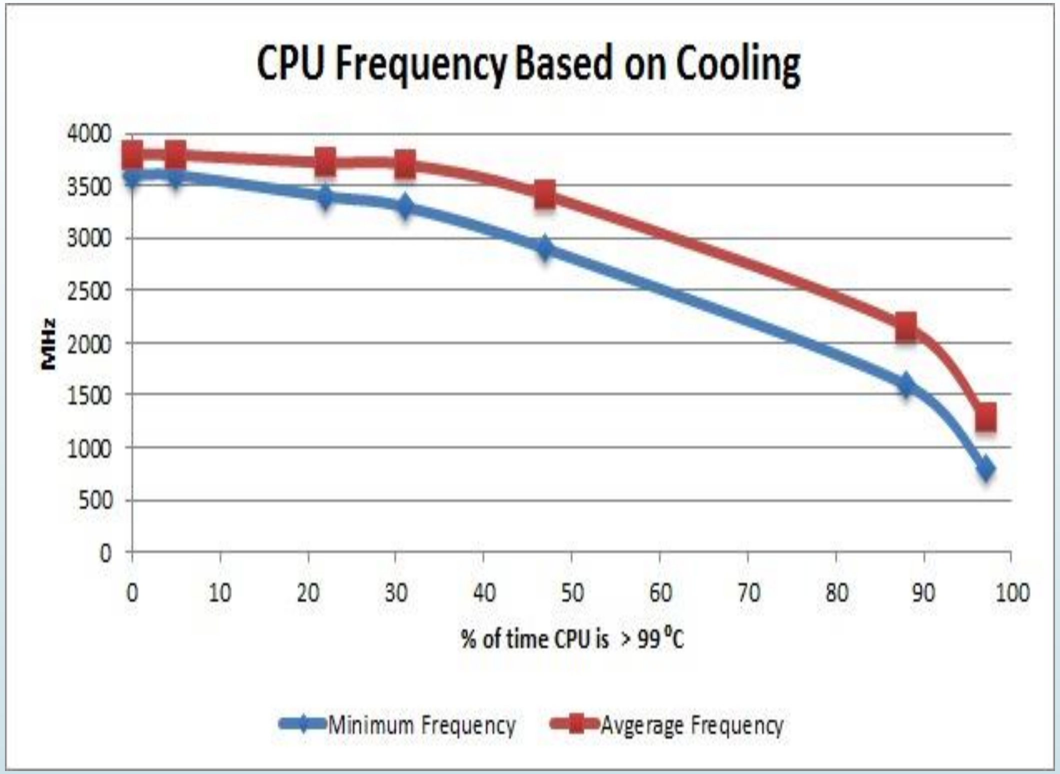
- Technology is a leading industry and is undergoing rapid developments
- UAE computer market was estimated around 15.75 billion AED in 2013
- It is expected that it will grow at a rate of 8.47% until 2018 (Dubai chamber, 2013)
- Computers should be able to:
  I. process more data in less time
  II. become smaller in size
  III. become more accessible
- 55% of all computer failures happen due to overheating
- Electronic devices cooling systems most coveted traits include:
  I. High effectiveness
  II. Have better performance
  III. Compact size

Problem Statement and Purpose

- In older CPUs overheating meant immediate failure, in modern ones it means a much slower system.

Purpose and objectives:

- building an enhanced cooling system for electronic devices
- Explore different configurations of cooling systems along with various cooling fluids that can be utilized within the design

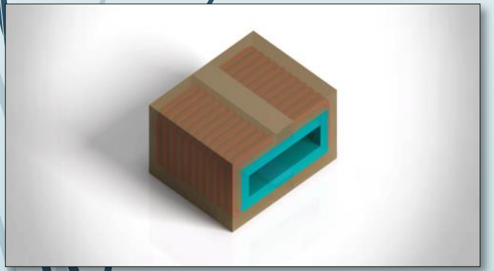


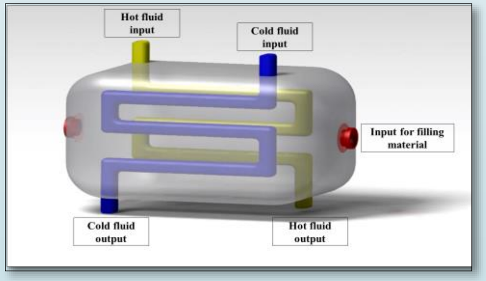
Effect of amount of time the CPU temperature was running at > 99 °C on frequency, courtesy of Intel corporation

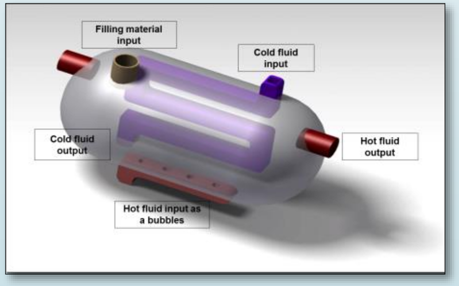
Proposed Conceptual Designs

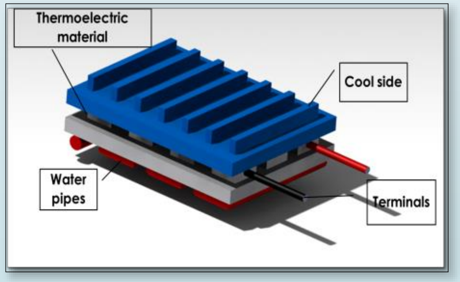
Proposed Conceptual Designs

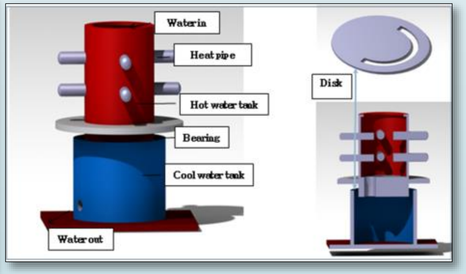
- Cooling using liquid metal and PCM as a heat sink
- Modified shell and tube heat exchanger
- Direct contact heat exchanger
- Thermoelectric plate
- Heat pipe cooling system



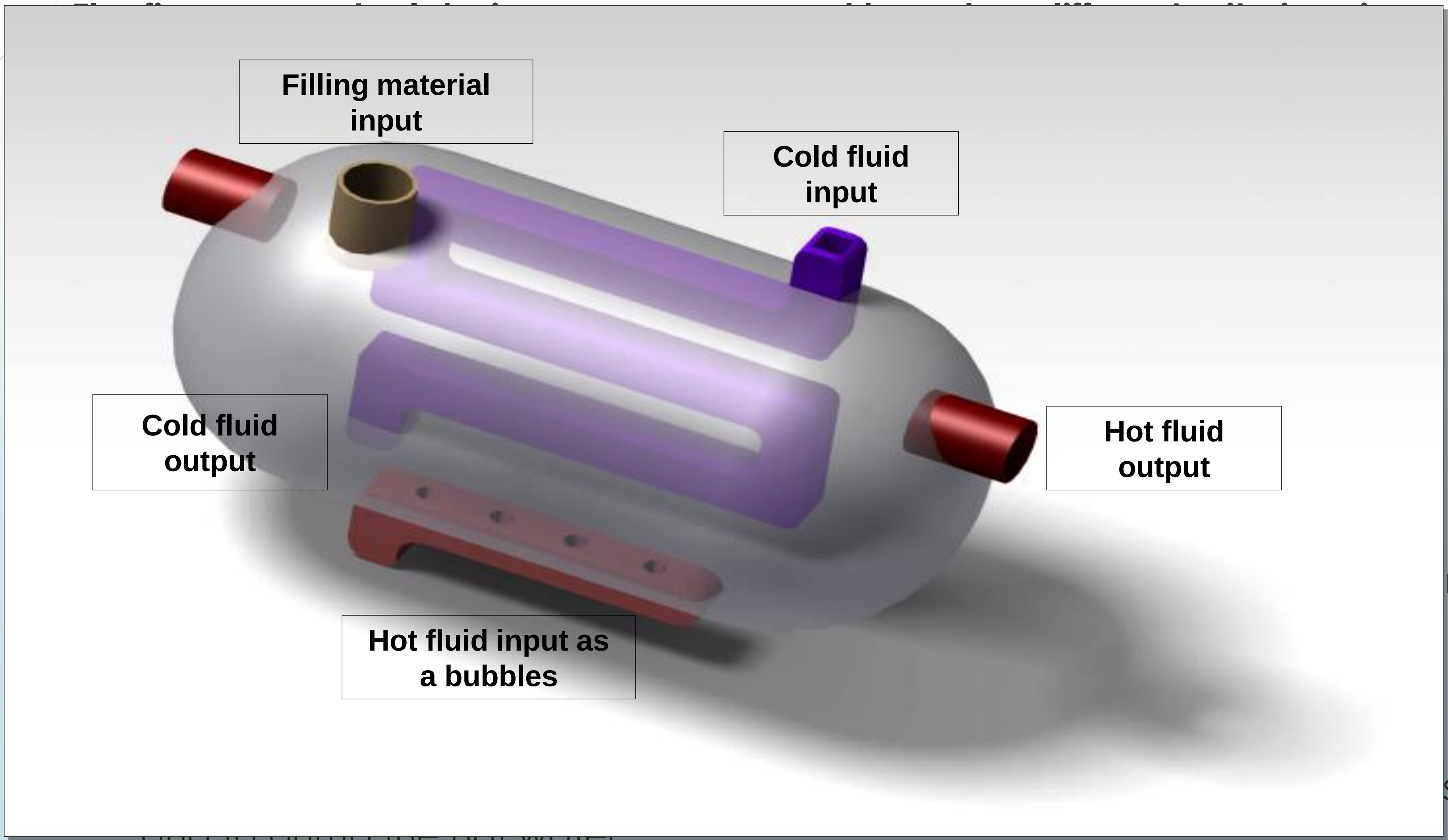








Selected Conceptual Design



and

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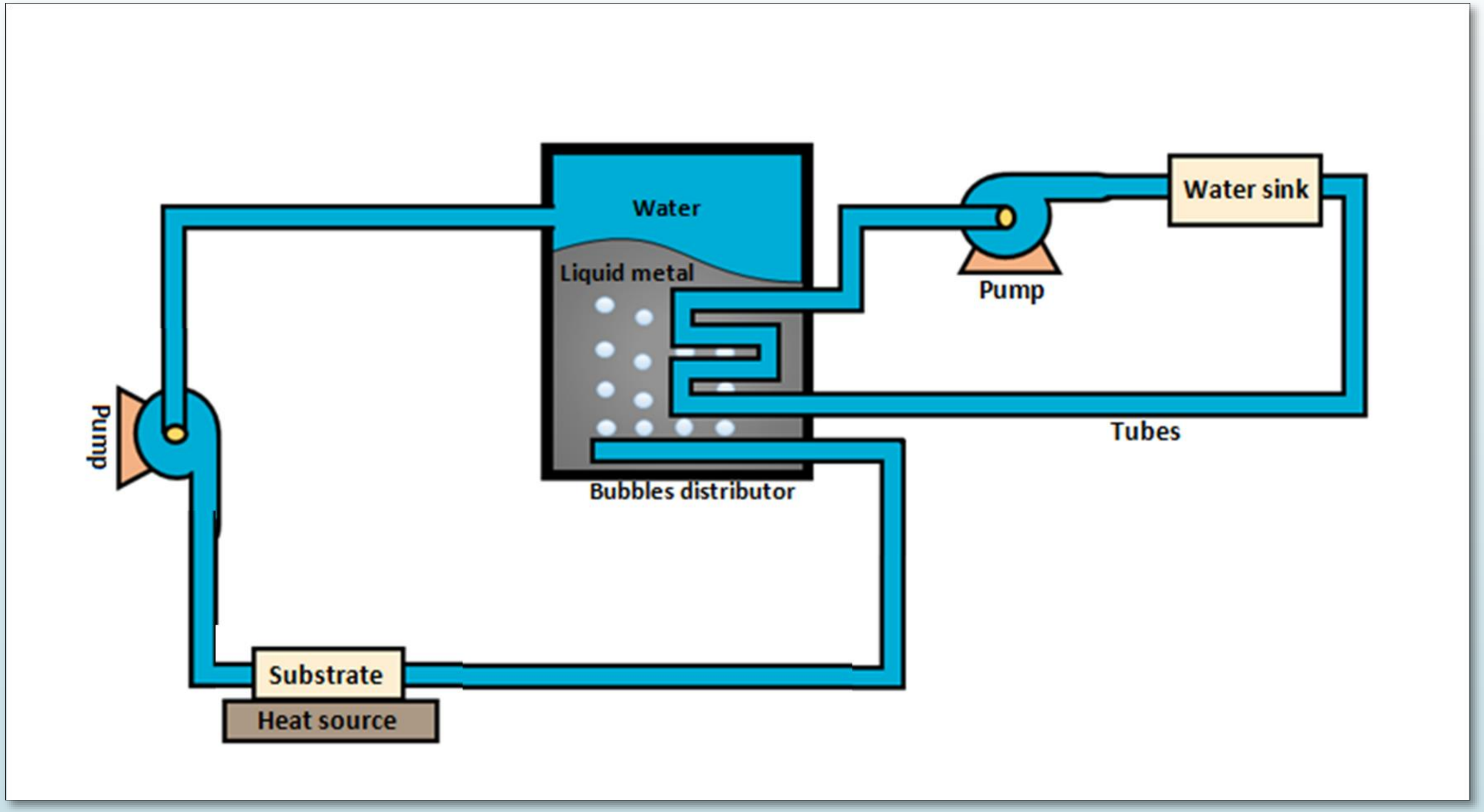
stem

and to pump the hot water

Embodiment Design

- **The system comprised of**
  - Substrate
  - Heat sink
  - Bubble distributor
  - Pump

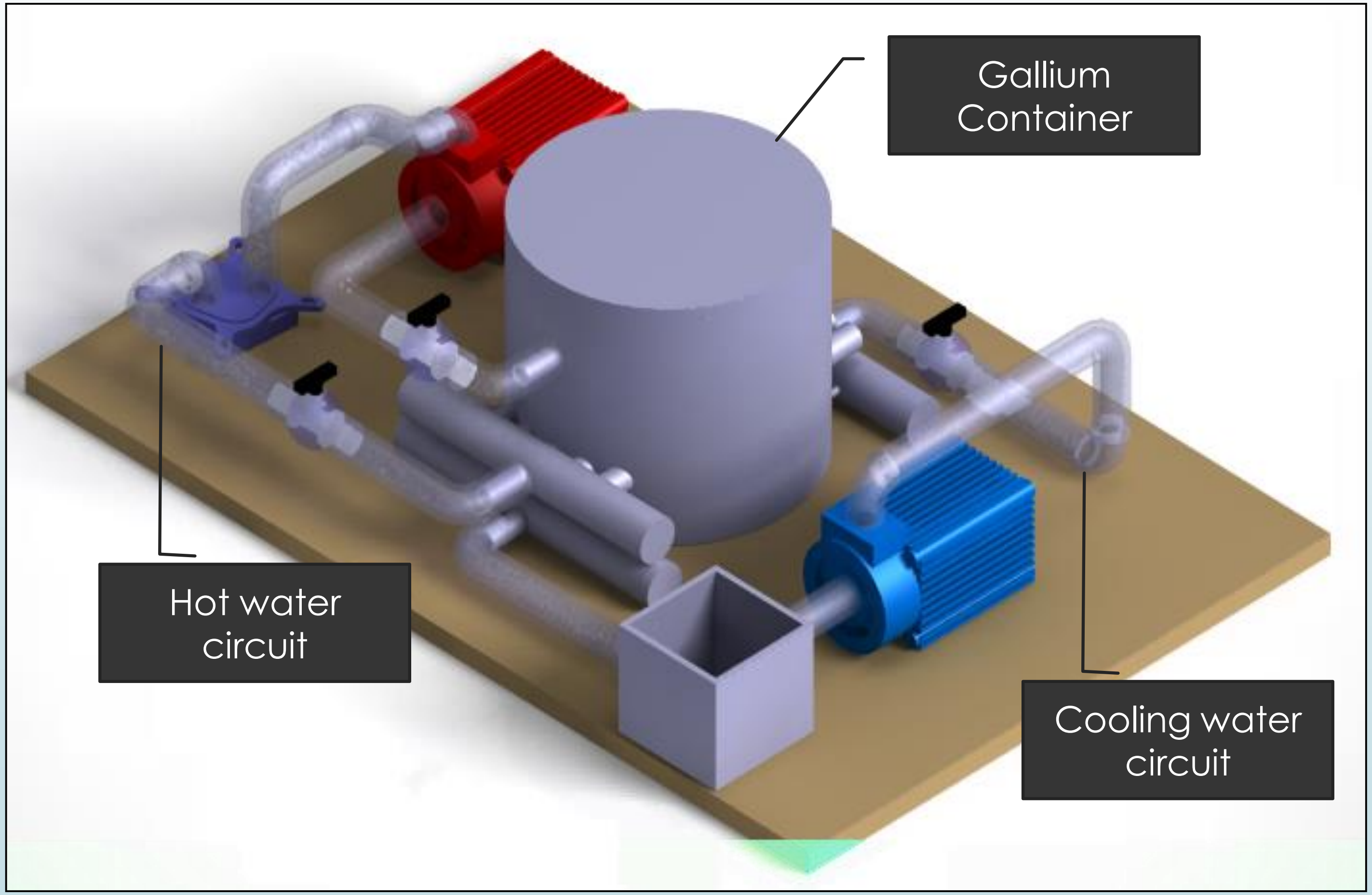


Relevant Literature Search

- Literature Review
  - Thermal interface material
  - Heat transfer and flow over sphere
  - Bubble dispersion
  - CISCO Company
  - Enhancement of heat transfer in electronic devices
    - Water co-flow with Liquid metal
    - Micro-channels with super hydrophobic surfaces
    - Phase Change Material composite heat sinks
    - Micro-Machined Porous Channels

Detailed level specifications

- The system consists of:
  1. Gallium container
  2. Hot water circuit which consists of:
     a. Hot water pump
     b. Substrate
     c. Bubble distributor
  3. Cooling water circuit which consists of:
     a. Cooling water pump
     b. Cooling water network
     c. Water reservoir



Detailed level specifications

- **Selection criteria:**

1. Selected pump should consider:
    - The required head
    - The required volumetric flow rate.
    - Noise level (<30dBA)

2. Selected substrate should:
    - Absorb the heat effectively
    - Maintain the CPU at the operational temperature

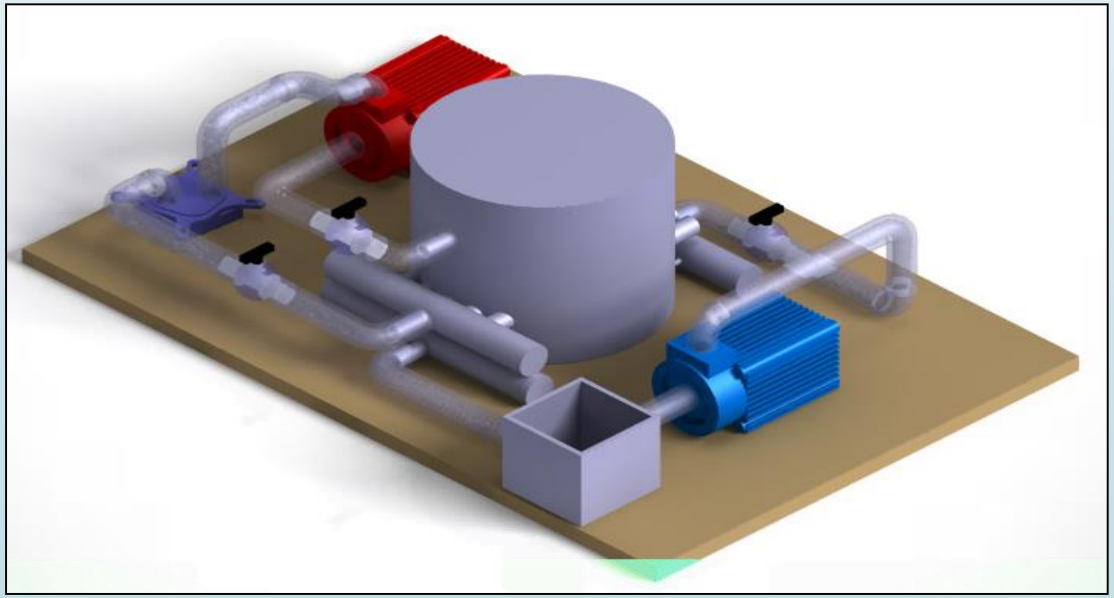
3. Selected material should
    - Compatible with gallium
    - Highly conductive

Relevant Engineering applications and calculations

- **System design calculations**

1. **Gallium container**
   a. Container dimensions
   b. Gallium height
2. **Hot water circuit:**
   a. Total head required (Hot water pump selection)
   b. Substrate configuration
   c. Water flow rate through the substrate
   d. Bubble distributor's
      i. Number of holes
      ii. Number of tubes

3. Cooling water circuit:
   a. Total head required (Cooling water pump selection)
   b. Cooling water network configuration
   c. Cooling water flow rate



Relevant Engineering applications and calculations

- **Cooling water circuit calculation**
  - Given Information:

Inlet temperature (Ti)	20 °C
Outlet temperature (Te)	25 °C
Tube diameter (D)	2 mm (Assumption)
Density (ρ)	995 kg/m3
Thermal conductivity (k)	0.619 W/m.K
Viscosity (μ)	7.98x10-4 Pa.s
Heat capacity (cp)	4018 W/°C
Prantl Number (Pr)	5.125

Relevant Engineering applications and calculations

- **Cooling water circuit calculation**

Varying the water mass flow rate ($\dot{m}_{CW}$) from 0.0001 kg/s until 0.06 kg/s

→

Testing the range for different number of tubes

→

Finding best combination of the mass flow rate and number of tubes to remove 340 W

Relevant Engineering applications and calculations

- **System design calculations**

1. Gallium container
   a. Container dimensions
   b. Gallium height
2. Hot water circuit:
   a. Total head required (Hot water pump selection)
   b. Substrate configuration
   c. Water flow rate through the substrate
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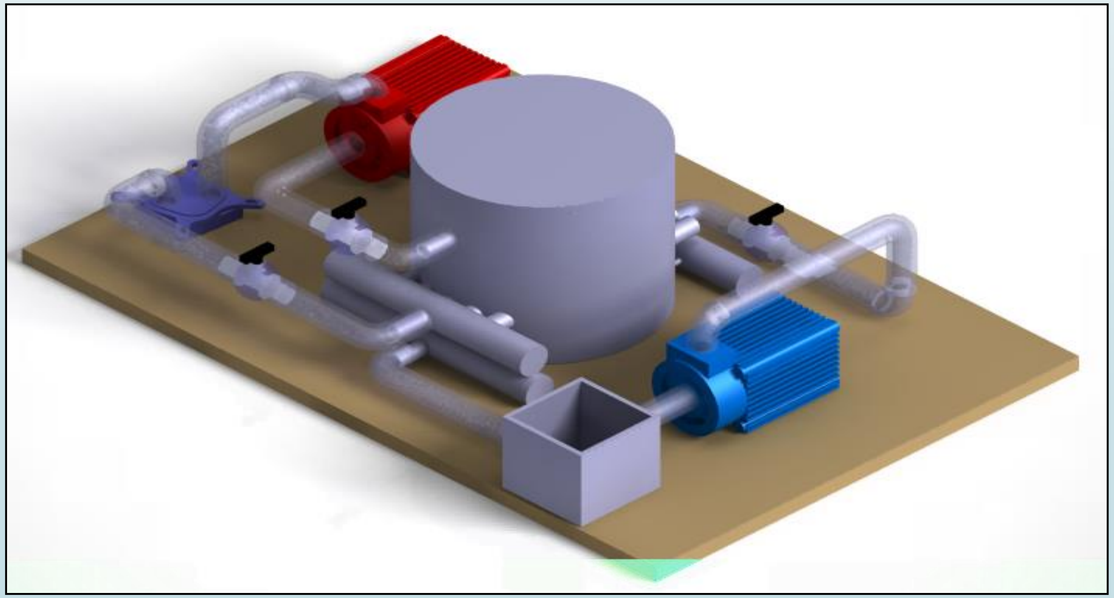
   c. Cooling water flow rate



Relevant Engineering applications and calculations

- **Hot water circuit calculation**
  - The same procedure was followed to find the mass flow rate in the substrate except:
    1. Inlet temperature (T_i)= 30 °C
    2. Outlet temperature (T_e)= 70 °C
    3. Tube length: 4 cm
  - **Hot water and cold water circuit conclusion:**

Circuit	Mass flow rate (kg/s)	Volumetric flow rate (LPM)	Number of tubes
Cooling water circuit	0.0481	2.9	5
Hot water circuit	0.0376	2.24	5

Relevant Engineering applications and calculations

- **System design calculations**

1. **Gallium container**
   a. Container dimensions
   b. Gallium height
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   a. Total head required (Cooling water pump selection)
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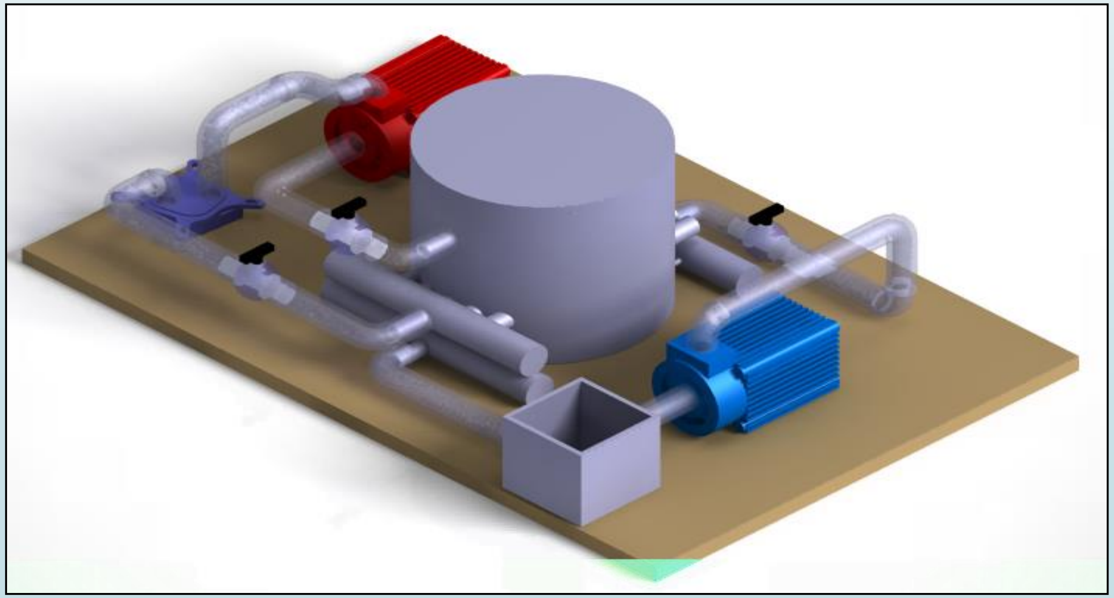


Relevant Engineering applications and calculations

- **Bubbling system Calculation:**
  - Given Information:

Inlet temperature (T_i)	70 C
Outlet temperature (T_e)	30 C
Gravitational acceleration (g)	9.81 m/s^2
Bubble radius (r)	1.5 mm
Water density (ρ_g)	985 kg/m^3
Gallium density (ρ_g)	5910 kg/m^3
Gallium viscosity (μ_g)	0.0015 Pa.s
Gallium thermal conductivity (k)	40.6 W/m.K

Relevant Engineering applications and calculations

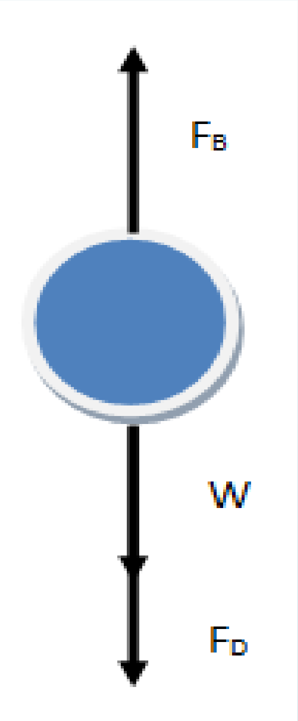
- **Bubbling system Calculation:**
  - To illustrate bubble motion inside gallium bath, Newton second law is applied:

$$\sum F = ma$$

$$F_B - W - F_D = ma$$

$$\rho_g v_w g - \rho_w v_w g - \frac{1}{2}\rho_g V^2 A C_D = ma$$

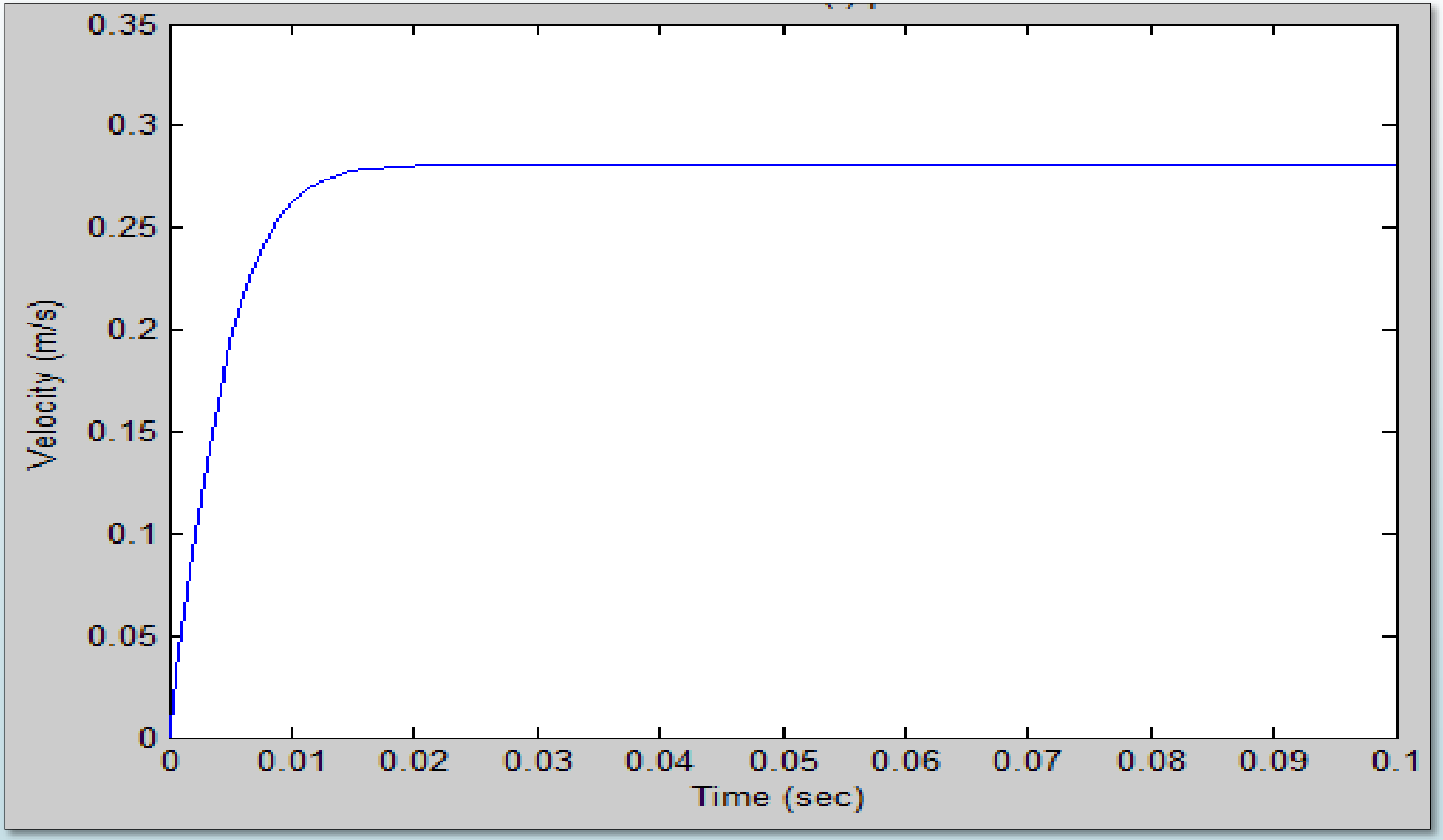
$$202x10^3 r^3 = 9.3x10^3 V^2 r^2 C_D + 4.2x10^3 r^3 \dot{V}$$



  - By using ODE45 and curve-fitting tool in MATLAB, the above equation was solved to get:

$$V = 0.2862 * e^{-0.2269t} - 0.288 * e^{-226\,t}$$

Relevant Engineering applications and calculations



Relevant Engineering applications and calculations

- **Bubbling system Calculation:**

Velocity

$$V = 0.2862 * e^{-0.2269t} - 0.288 * e^{-226\,t}$$

↓

Reynolds Number

$$Re = \frac{\rho_g v D}{\mu_g}$$

↓

Nusselt Number

$$Nu = 2 + \left[0.4 Re^{\frac{1}{2}} + 0.06 Re^{\frac{2}{3}}\right] . \mathrm{Pr}^{0.4} \left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

↓

Heat transfer coefficient

$$U = Nu * \frac{D}{k}$$

↓

Heat transfer

$$\dot{Q} = U A_s (T_i - T_s)$$

Relevant Engineering applications and calculations

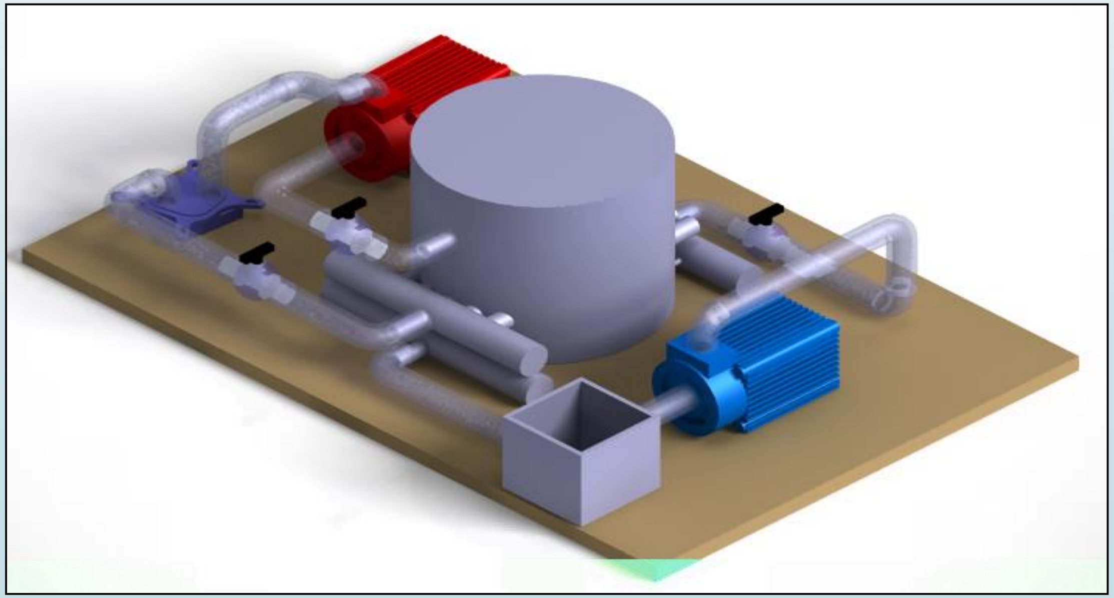
- **Bubbling system Calculation:**
  - **It found that a single bubble:**
    - ✓ Took 0.185 sec to drop its temperature from 70 °C to 30 °C
    - ✓ Losses 2.5 J
  - **The total number of bubbles needed is** 3430 bubbles/s
  - **Single pass, gives minimum container length of** 123 mm
  - **The total distance travelled by the water bubble through liquid gallium is** 50.7 mm

Relevant Engineering applications and calculations

- **System design calculations**

  1. Gallium container
     a. Container dimensions
     b. Gallium height
  2. Hot water circuit:
     a. Total head required (Hot water pump selection)
     b. Substrate configuration
     c. Water flow rate through the substrate
     d. Bubble distributor's
        i. Number of holes
        ii. Number of tubes

3. Cooling water circuit:
   a. Total head required (Cooling water pump selection)
   b. Cooling water network configuration
   c. Cooling water flow rate



Relevant Engineering applications and calculations

Pump selection

- To select suitable pumps for the system, the total required system head versus the volumetric flow rate must be plotted.

water velocity → Volumetric flow rate → Total head for each velocity.

Relevant Engineering applications and calculations

➨ Pump selection

- ***The head required in this system is due to several factors which are:***

1. *Major head loss in the tubes:*

$$H_{loss_{major}} = f\frac{L}{D}\frac{V^2}{2g}$$

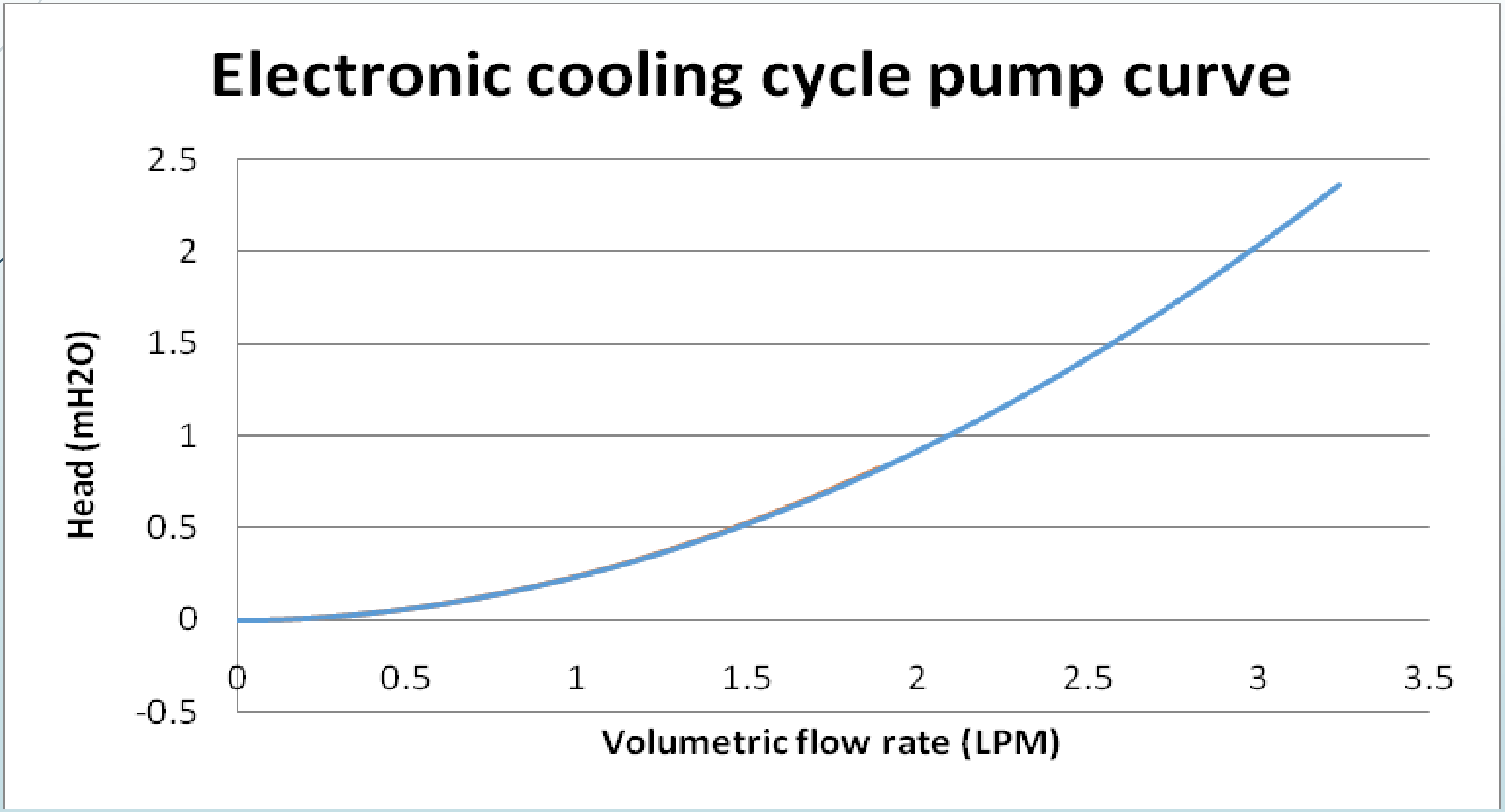
2. Minor head loss due to the pipe fittings:

$$H_{minor} = \sum K_L \frac{V^2}{2g}$$

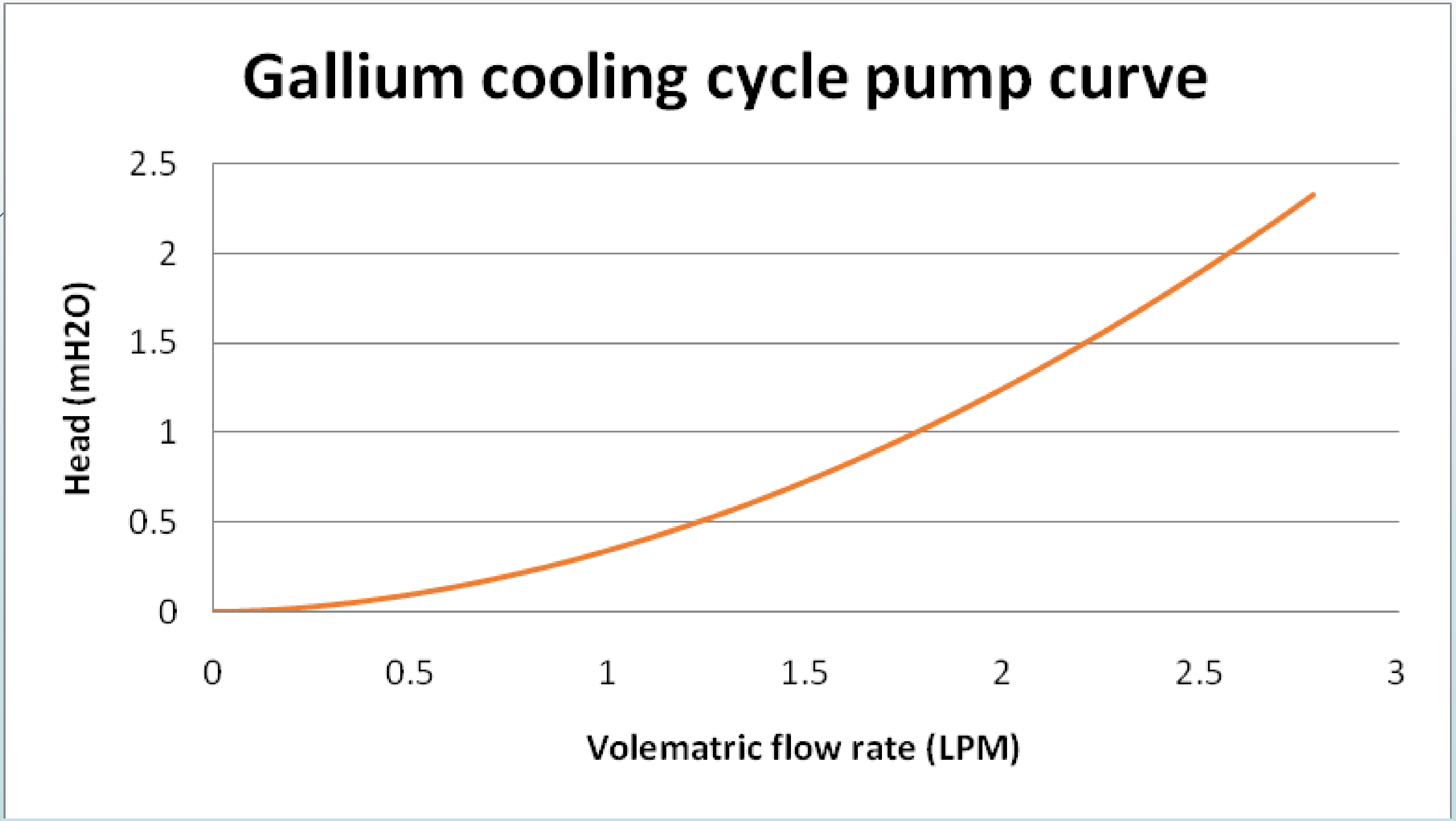
3. *Head required due to overcome the gallium height above bubbler*

4. *Head required due to elevation*

Relevant Engineering applications and calculations

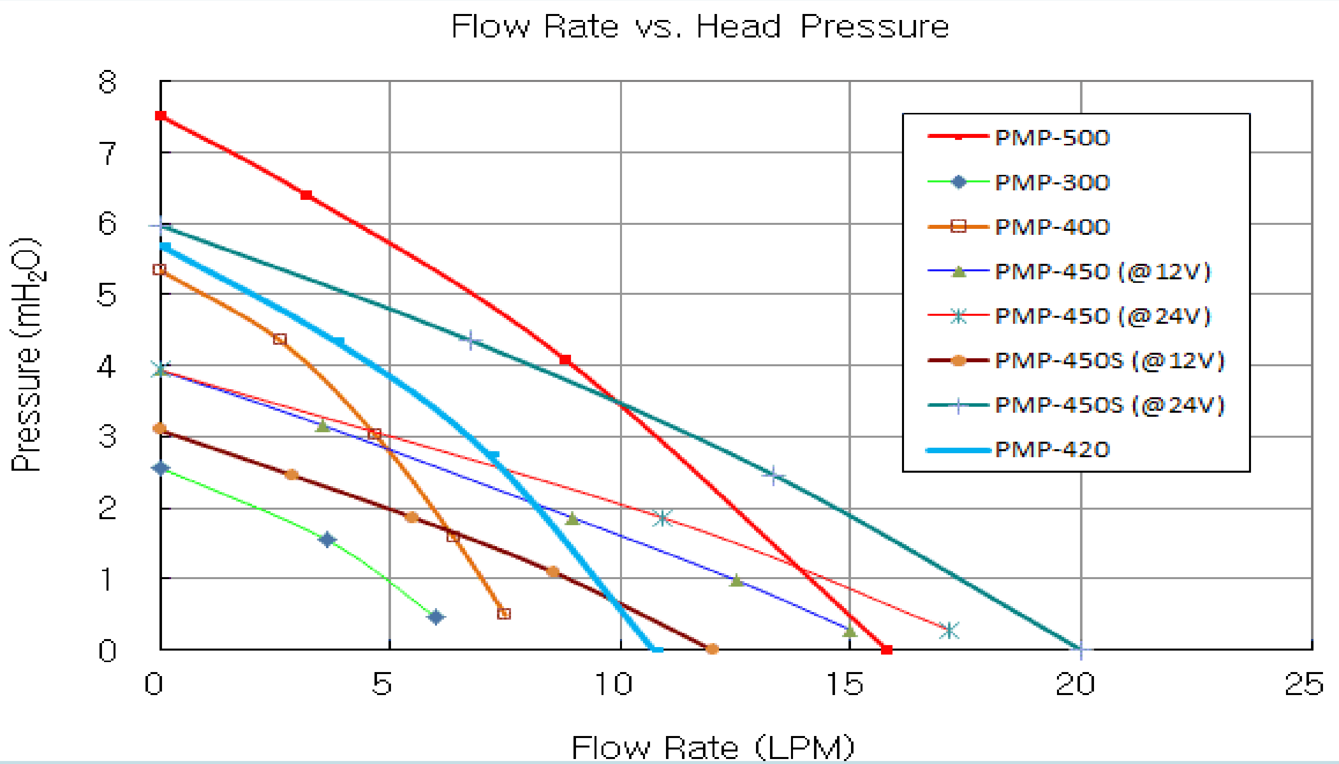


Relevant Engineering applications and calculations



Relevant Engineering applications and calculations

- **Pump selection**
  - Intersect the system curves and pump performance curves



Relevant Engineering applications and calculations

- **Pump selection**

Model	Maximum Flow Rate	Maximum Head Pressure	Power Consumption	Voltage	Noise	Weight
PMP 420	11L/min	5.8 m	17W	6 to 12 VDC	<50dBA	284g

Discussion of Detailed Design alternatives

Heat source	Liquid metal used	Cooling method of the liquid metal	bubbling system used
• Hot Plate • Infrared Heater • Hot water tank	Mercury Gallium Sodium	• Air cooling using a fan • Cooling tubes embedded within the gallium • Submersion of the system in a water reservoir	• Distribution plate • Helical bubbling system • Distribution tube with several branches

Formal Decision-Making , Heat Source

		Alternatives					
Decision Model		Hot Plate		Infrared Heater		Hot water Tank	
Criterion	Weight	Rating	Score	Rating	Score	Rating	Score
Availability	5	4	20	4	20	5	25
Simplicity	5	2	10	3	15	4	20
Integration	10	3	30	2	20	4	40
Total	20	9	60	9	55	13	85

Formal Decision-Making, Liquid metal

		Alternatives					
Decision Model		Mercury		Gallium		Sodium	
Criterion	Weight	Rating	Score	Rating	Score	Rating	Score
Cost	5	2	10	3	15	4	20
Toxicity	5	1	5	4	20	2	10
Thermal Conductivity	10	7	70	9	90	8	80
Thermal Capacity	10	6	60	8	80	9	90
Melting Temperature	5	4	20	4	20	1	5
Total	20	20	165	27	225	24	214

Formal Decision-Making, Cooling method of the liquid metal

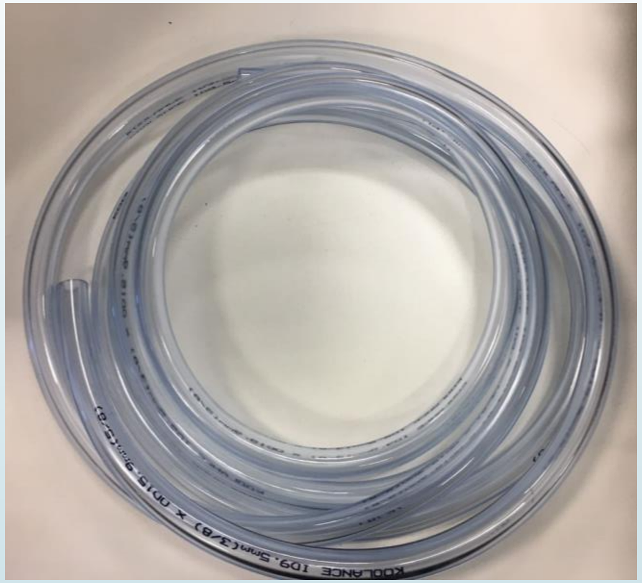
		Alternatives					
Decision Model		Fan		Cooling water tubing		Submersion	
Criterion	Weight	Rating	Score	Rating	Score	Rating	Score
Availability	5	3	15	4	20	5	25
Simplicity	5	3	15	2	10	4	20
Integration	10	7	70	8	80	6	60
Total	20	13	100	14	110	15	105

Formal Decision-Making, Bubbling system

		Alternatives					
Decision Model		Distribution plate		Helical bubbling system		Distribution tube	
Criterion	Weight	Rating	Score	Rating	Score	Rating	Score
Manufacturability	5	3	15	2	10	4	20
Number of holes available	5	4	20	3	15	4	20
Heat Dissipation	6	3	18	5	30	5	30
Total	16	10	53	10	55	13	70

Methods of realizing final design

- Item purchased



Valves

Fittings

Rubber Tubes

Methods of realizing final design

- Item purchased

Pumps

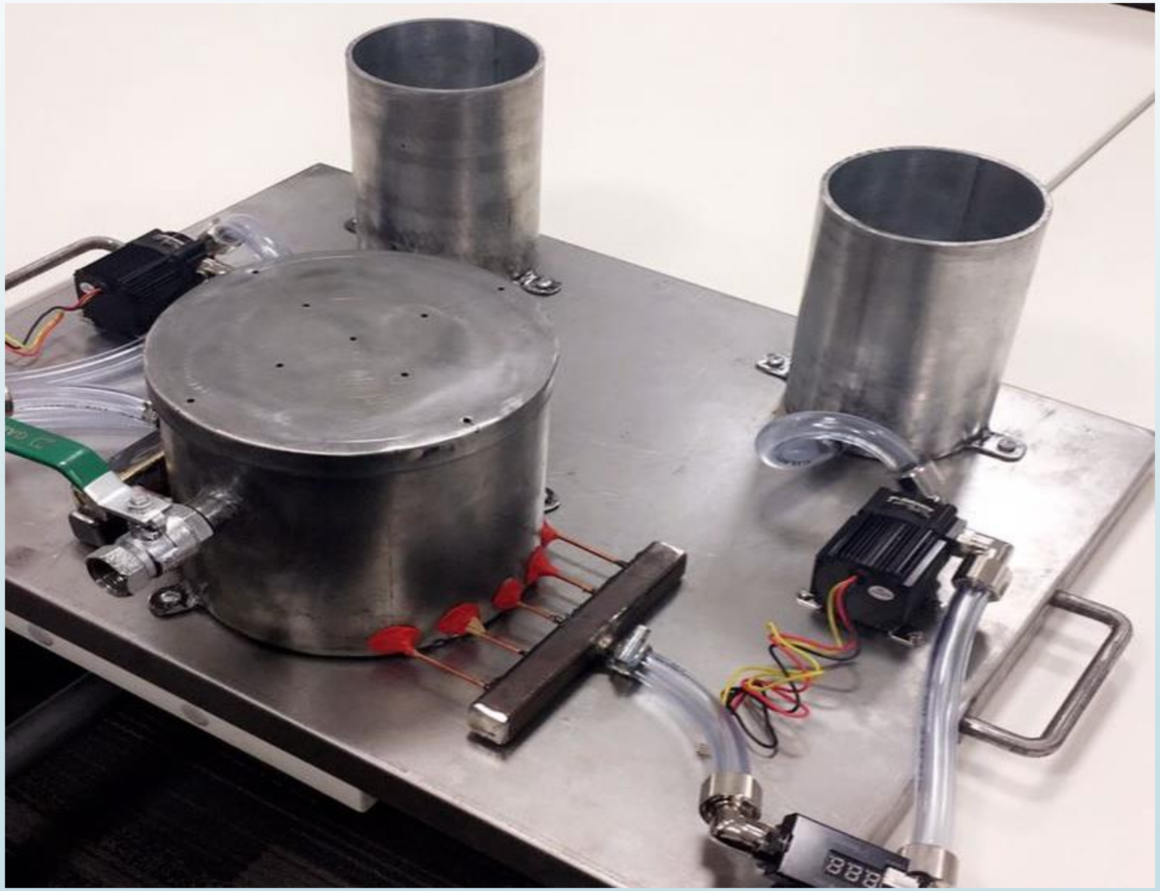
Copper Tubes

Methods of realizing final design

- System configuration

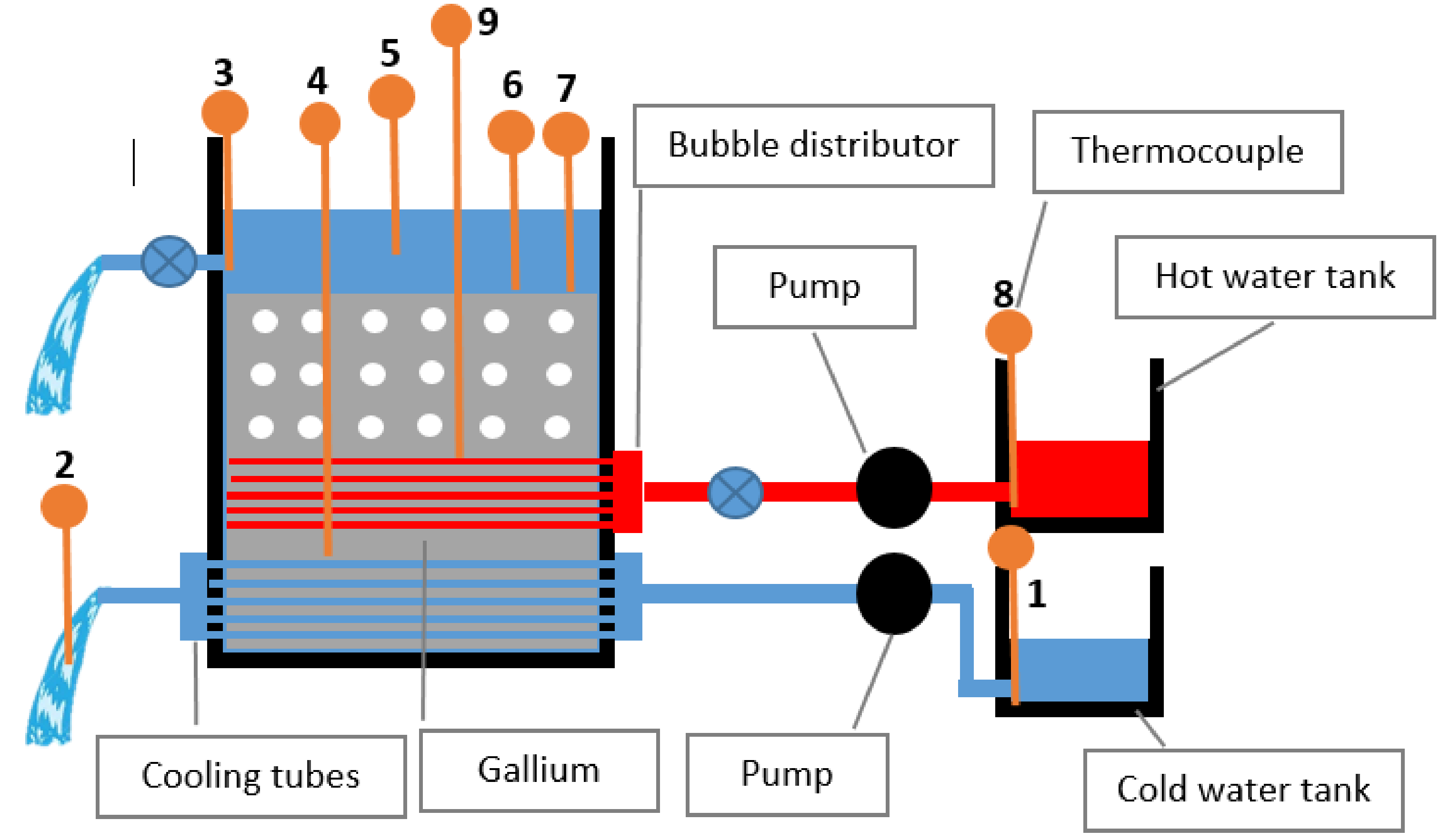
Methods of realizing final design

- **System configuration**



Testing

- Testing setup



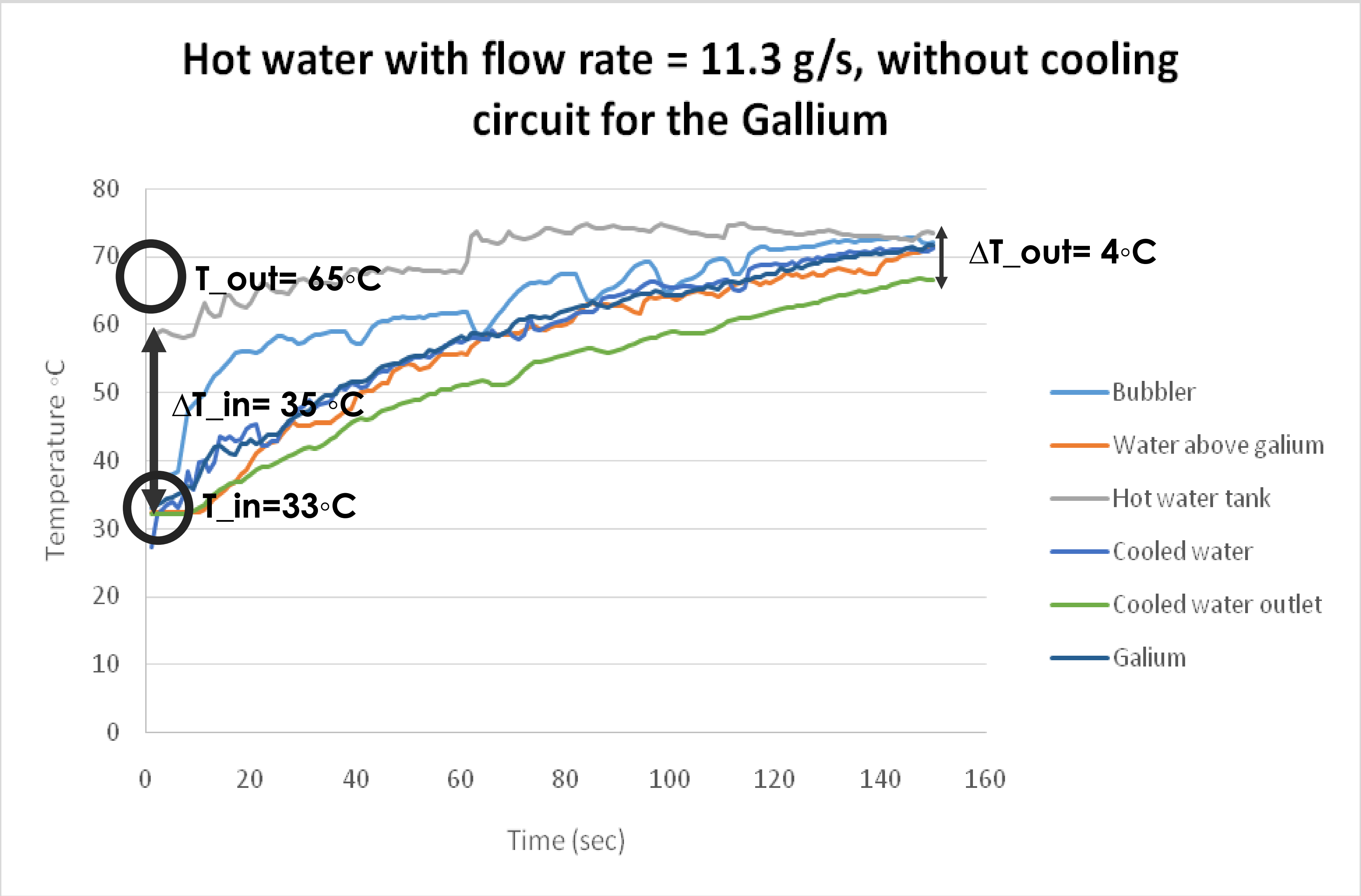
Testing

- Tested flow rate

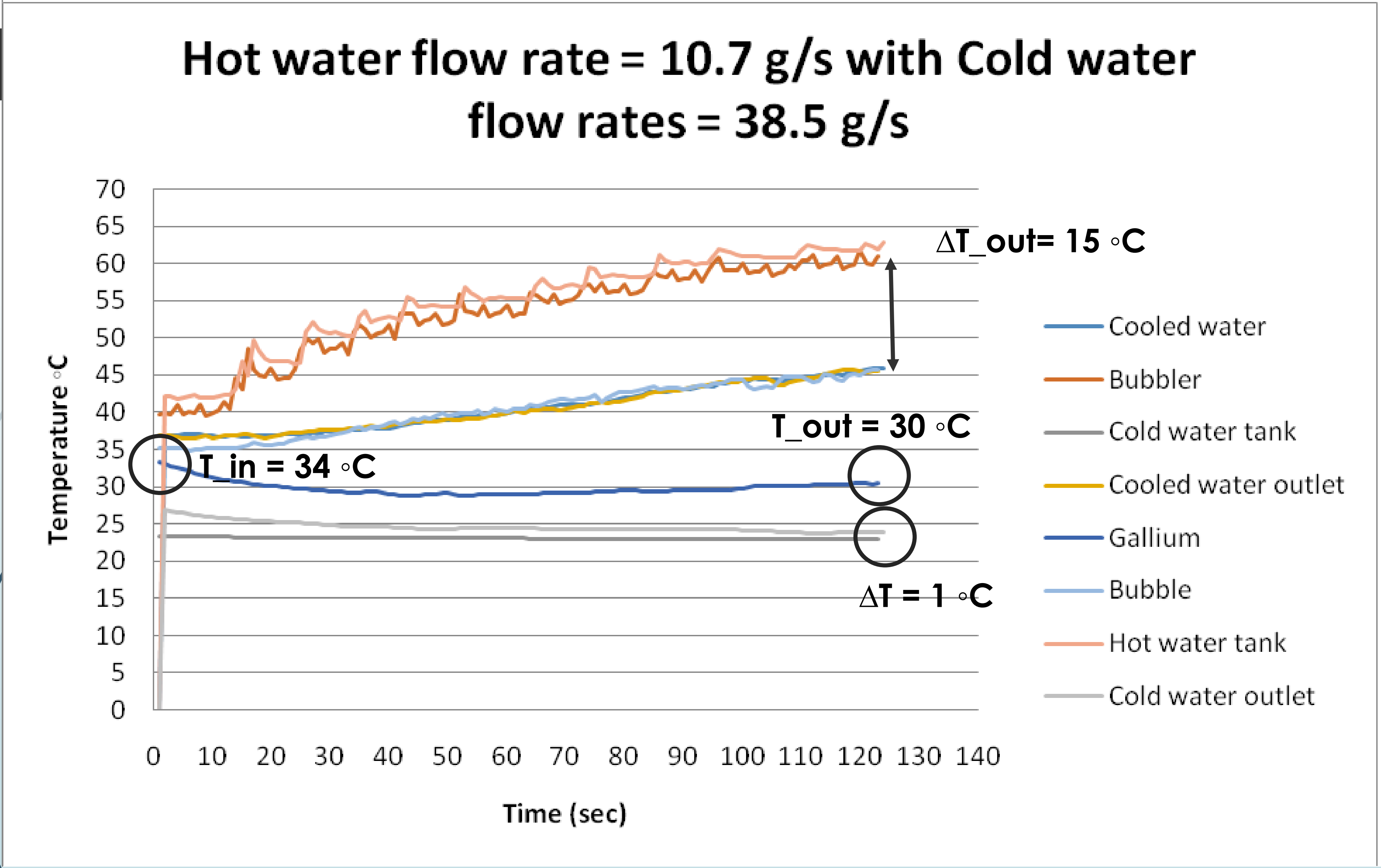
Pump	Supplied Voltage (Volt)	Flask volume (mL)	Time (sec)	Flow rate (g/s)	Average flow rate (g/s)
Hot water pump	6.3	250	21.81	11.46	11.26
			22.61	11.06	
	6		23.61	10.59	10.72
			23.05	10.85	
Cold water pump	6.5		7.81	32.01	33.10
			7.31	34.20	
	7.5		6.44	38.82	38.52
			6.54	38.23	

Analysis and Optimization

- **The designed system was tested under different cases to check its effectiveness. Three different cases were considered to investigate the performance of the designed system as follows:**
  - Hot water flow-rate of 11.3 g/s and 12.3 g/s without using the gallium cooling circuit
  - Hot water flow-rate of 10.7 g/s with cold water flow rate of 33.1 g/s and 38.5 g/s
  - Hot water flow-rate of 11.3 g/s with cold water flow rate of 33.1 g/s and 38.5 g/s


Hot water with flow rate = 11.3 g/s, without cooling circuit for the Gallium
T_out= 65◦C
ΔT_in= 35 ◦C
T_in=33◦C
ΔT_out= 4◦C
Temperature ◦C
Time (sec)
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140
160
Bubbler
Water above galium
Hot water tank
Cooled water
Cooled water outlet
Galium

ing

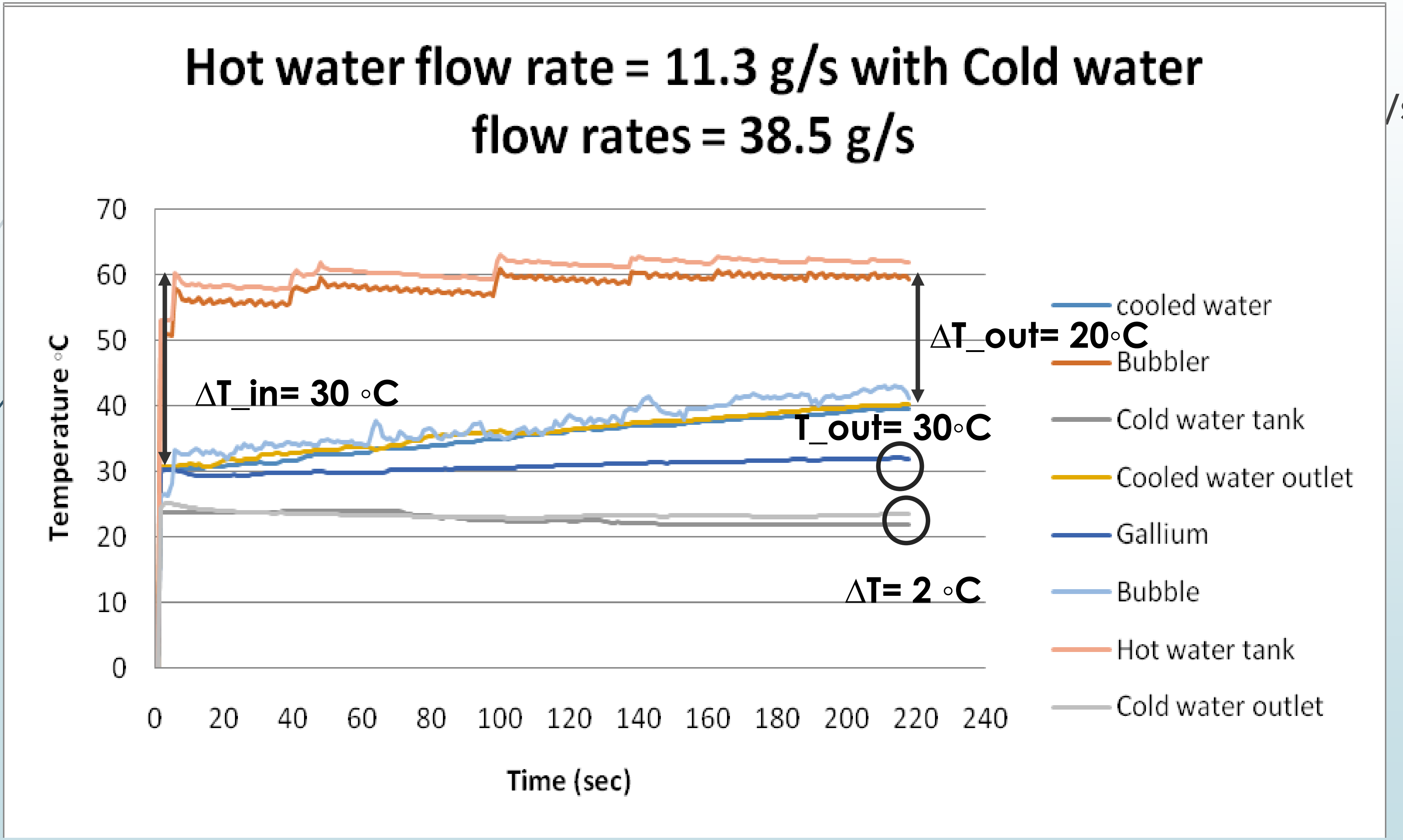


Hot water flow rate = 10.7 g/s with Cold water flow rates = 38.5 g/s
Temperature ◦C
Time (sec)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
ΔT_out= 15 ◦C
T_out = 30 ◦C
T_in = 34 ◦C
ΔT = 1 ◦C
Cooled water
Bubbler
Cold water tank
Cooled water outlet
Gallium
Bubble
Hot water tank
Cold water outlet

and

Analysis and Optimization

/s and



Analysis and Optimization

Case #	Hot water Flow rate (g/s)	Cold water Flow rate (g/s)	Cooled water Temperature difference (◦C)	Gallium Temperature difference (◦C)	Cold water Temperature difference (◦C)
1	11.3	-	4	32	-
2	12.3	-	3	40	-
3	10.7	33.1	10	8	1
4	11.3	33.1	15	4	1
5	10.7	38.5	11	3	1
6	11.3	38.5	20	~0	2

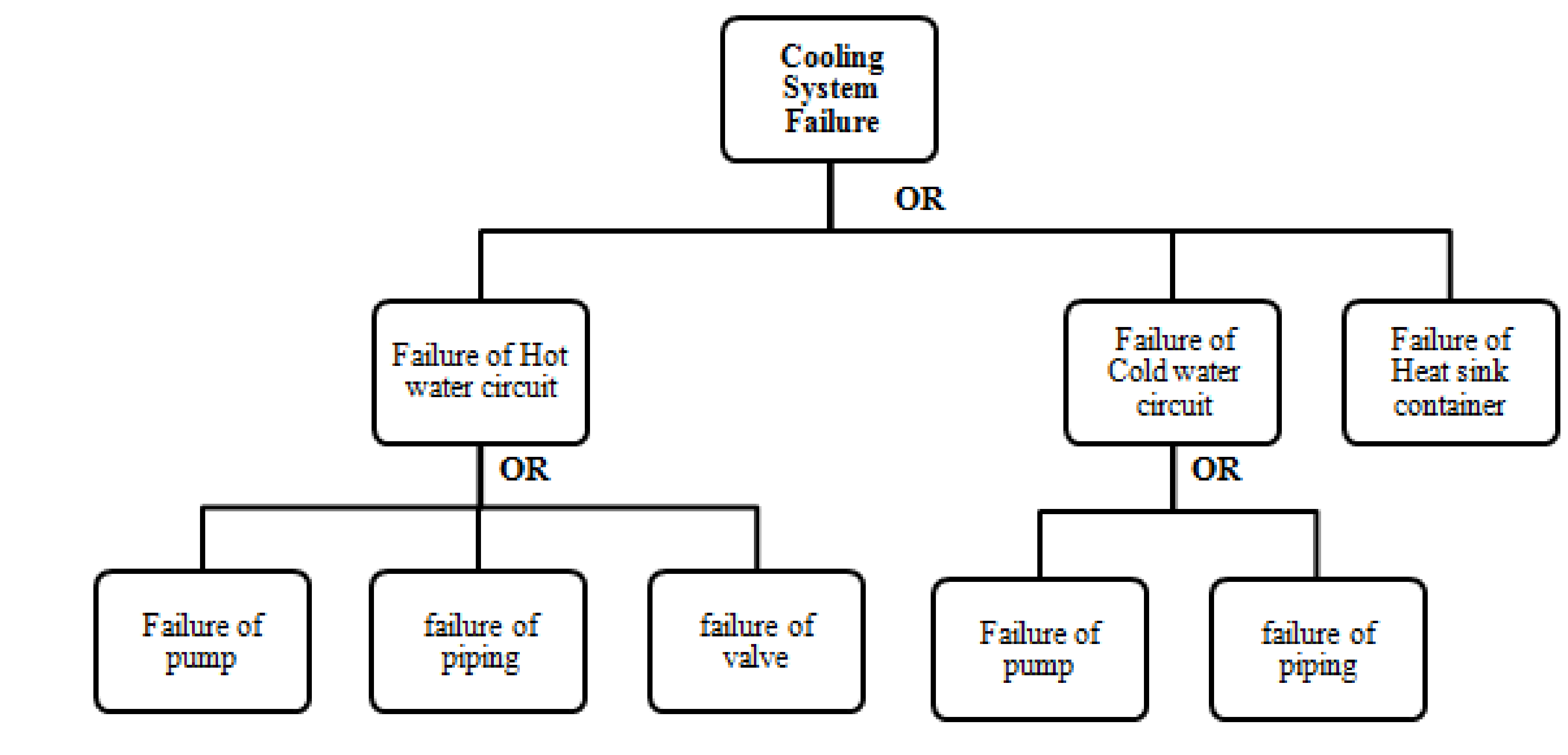
Final Cost Analysis and Discussion

Component	Quantity	Price (AED)
Gallium	6 kg	5,700
Rubber tubes	3 m	53
Copper tubes	2 m	20
Gallium cooling pump	1	220
Electronics cooling pump	1	220
Valve	2	55
Fittings	8	60
Hose clamps	4	4
Manufacturing	-	1,000
Total		7,332

Health, Safety, Quality, and Reliability

Component or process	Failure mode/s	Failure Effect/s	Safety Procedure/s
Addition of water to the system	Slipping risk	Several Injuries including back injury and fractures	• Wearing Personal Protective Equipment (PPE) • Clear precautionary signs in case of wet floor
	Spilling of water on electrical components	Electrocution	Immediate shut down of the system in case water reaches the electrical components
Addition of liquid metal to the system	Spilling or leakage of liquid metal	Contamination	• Wearing Personal Protective Equipment (PPE) • Keep away from water, food, animals and children reach
Pump	Failure of the mechanical components of the pump	• Physical harm • Harm to system components	• Add separate control switches for the pumps • use of data acquisition system to monitor the pumps
Container and piping system	• Rupture • leakage	• Electrocution • System shutdown	• Monitoring of leakage in the system • Proper leakage prevention through insulation

Health, Safety, Quality, and Reliability



Health, Safety, Quality, and Reliability

- For the Hot water circuit:

$$R_{c,1} = R_{pump}(1000) \times R_{valve}(1000) \times R_{pipies}(t)$$

$$R_{c,1} = 0.9386$$

- For the Cooling water circuit:

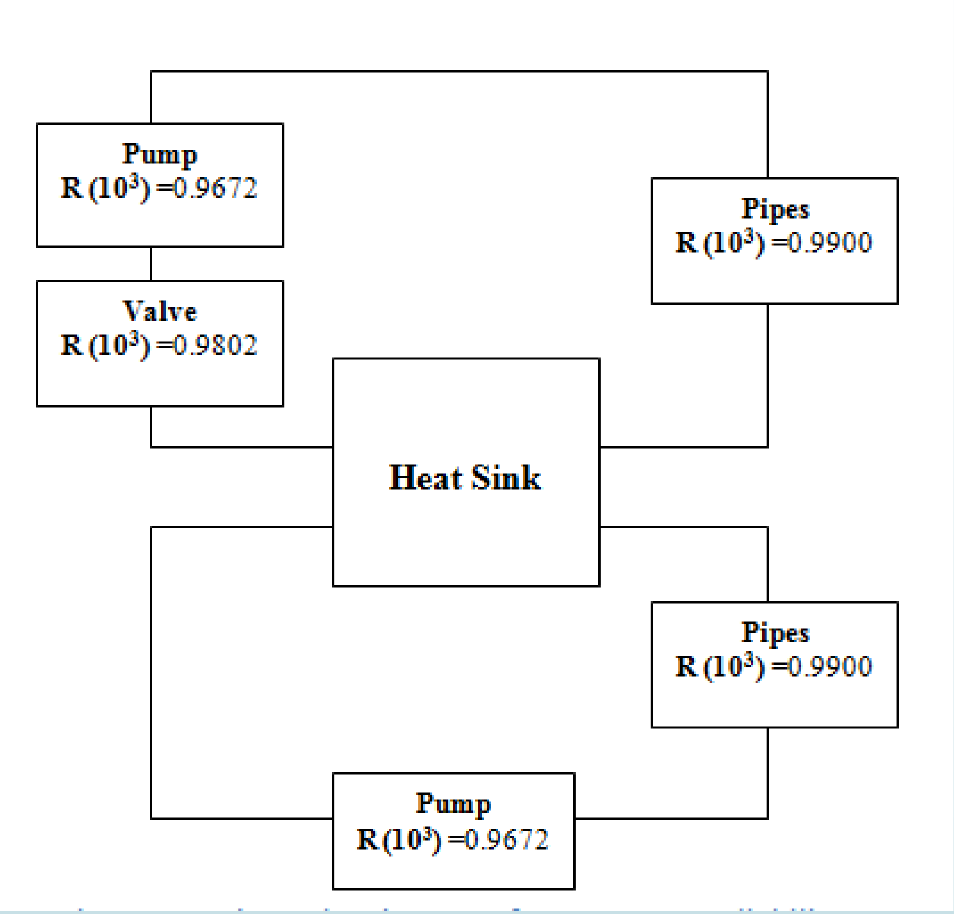
$$R_{c,2} = R_{pump}(1000) \times R_{pipies}(t)$$

$$R_{c,2} = 0.9575$$

- For the system:

$$R_s(t) = 1 - (1 - R_{c,1})(1 - R_{c,2})$$

$$R_s(t) = 0.9974$$



Performance evaluation

Requirement	Design Specification			Achievement
	Metric	**Value**	**Units**	
Good temperature control	• CPU operational temperature limit	< 75	°C	Yes
Cost	• Within the rang if current cooling system price	<3000	DHs	No
Reasonable cost	• Benefit to Cost ratio	≥ 1.3	-	No
Safe to use	• Safety Factor	>1.5	-	Yes
Eco- friendly	• Use materials with low toxicity levels • System Can be easily recycled	-	-	Yes
Quiet with Low vibration	• Appropriate Noise levels	<30	dBA	No
Availability of spare parts	• Use standard parts as advised by ASTM and IEEE -SA	-	-	Yes
Effective heat removal	• Heat Absorbed	>340	W	Yes
Reasonable life cycle	• Design life	25	Years	Yes
Low power consumption	• Power usage effectiveness	<1.18	-	Not applicable

Performance evaluation

- Comparison between the proposed cooling system (case 3) and the traditional cooling system :
- System parameters:
  - $T_{HW_{in}} = 60^{o}C$
  - $T_{HW_{out}} = 40^{o}C$
  - $T_{CW_{in}} = 22^{o}C$
  - $\dot{m}_{HW} = 11.3\ g/s$
  - $\dot{m}_{CW} = 38.5\ g/s$
  - $C_p = 4.18\frac{kW}{K}$
  - $U = 455\frac{W}{m^2}.K$
  - $\dot{m}_{HW_{one\ hole}} = \frac{11.3}{58} = 0.195\ g/s$
  - $\dot{m}_{CW_{one\ hole}} = \frac{38.5}{58} = 0.66\ g/s$

Performance evaluation

- The hot and cold fluids heat capacity rates can be found from:

$$C_h = \dot{m}_{HW} C_p = 0.195 * 4.18 = 0.82\ W/K$$

$$C_c = \dot{m}_{CW} C_p = 0.66 * 4.18 = 2.76\ W/K$$

- Therefore

$$C_{min} = 0.82 \frac{W}{K}$$

$$c = \frac{C_{min}}{C_{max}} = \frac{0.82}{2.76} = 0.3$$

- Maximum heat transfer rate is determined from:

$$\dot{Q}_{max} = C_{min} * \left(T_{HW_{in}} - T_{CW_{in}}\right) = 0.82 * (60 - 22) = 31.2\ W$$

Performance evaluation

- The actual rate of heat transfer in the heat exchanger is:

$$\dot{Q} = \dot{m}_{HW} C_p * \left(T_{HW_{in}} - T_{HW_{out}}\right) = 0.195 * 4.18 * (60 - 40) = 16.3\ W$$

- The effectiveness of the heat exchanger is

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{16.3}{31.2} = 0.52$$

- The number of transfer unit (NTU) can be found as follows:

$$NTU = \frac{1}{c-1}\ln\left(\frac{(\varepsilon - 1)}{\varepsilon c - 1}\right) = \frac{1}{0.3-1}\ln\left(\frac{(0.52-1)}{0.3 * 0.52 - 1}\right) = 0.81$$

Performance evaluation

- The required surface area is

$$A_s = \frac{NTU}{U} C_{min} = \frac{0.81}{455} * 0.82 = 1.46x10^{-3}\ m^2$$

- Using a tube diameter of 3 mm which is like the bubble hole diameter yield

  to a heat exchanger tubing length of:

$$\mathrm{L} = \frac{\mathrm{A_s}}{\pi \mathrm{D}} = \frac{1.46\mathrm{x}10^{-3}}{\pi\mathrm{x}3\mathrm{x}10^{-3}} = 15.5\ cm$$

- The needed length in the traditional cooling method is 13% longer than the proposed design

Environmental Analysis and Discussion

- **Several environmental issues that might arise;**
  - Pollution
  - heavy metal toxicity
  - electronic waste
- **Solutions:**
  - Insure that the final product is sustainable
  - Insure that there is no direct exposure of the users to the gallium in the heat sink
  - include a leakage detection system in the final product
  - Providing clients with the right channels to dispose their products

New skills learnt

- Integration of the numerous engineering skills in a single project
- Great opportunity to learn more about the engineering design process
- Great networking opportunity
- introduced to new topics in Mechanical engineering and state of the art cooling methods
- Enhanced problem solving skills
- Enhanced our Design of Experiment (DOE) skills

Way forward Final Discussion and remarks

- **Conduct further studies in the field of noble cooling systems for electronic devices**
- **More exploration of various bubbler geometries and their effect on heat removal**
- **Several improvements can be implemented to the system including:**
  - Addition of a dynamic control system
  - Several sensors, on/off controllers and check valves can be added
  - Sizing down the system
  - Decrease the overall cost of the system

Thank You

Any Questions ?