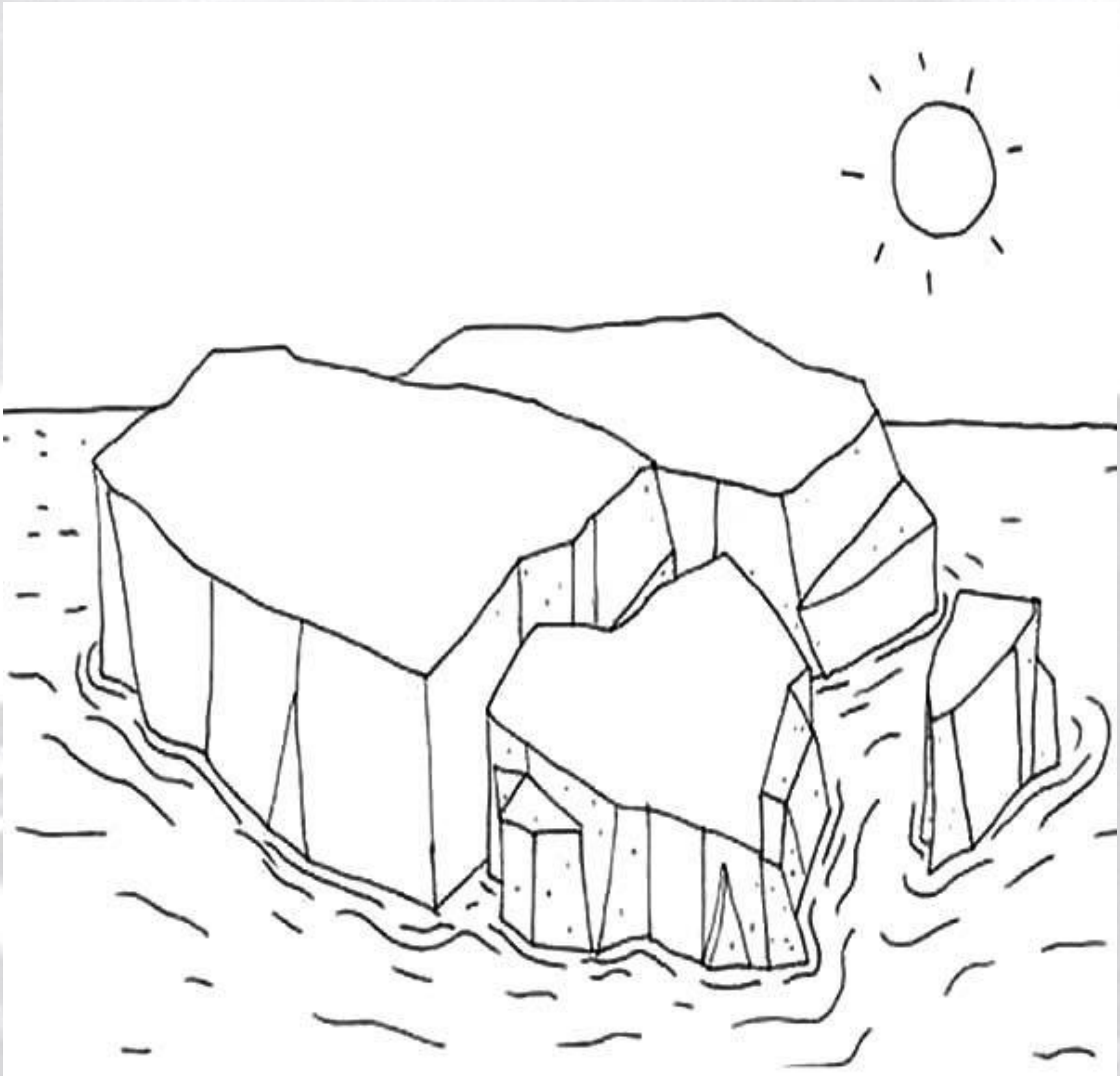
EP1: Rube Goldberg

Group 14

"Boling Ice Land"



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Introduction

My major is Chemical Engineering, I am interested in it so I chose this as my field of design. In the daily world, chemical engineering takes part in many important industries, from energy generation to pharmaceutical industries etc. These processes include sophisticated control for instance, gas pressure and fluid dynamics. Therefore, I hope I can have different fluid states as elements in my design.

My module is called the ‘Boiling Ice Land’, by putting the two extreme conditions together and seeing how they interact and work. This steamy and icy module will be one of the middle pieces of our group’s RG machine, which acts as a part to ensure the safe and smooth transfer of linkages between models. The linkage in my model is a ball which can link my model to the others. The ball (named ball 1) from Isabel’s model will be pushed by the blades and fall into mine. Then, another ball (named ball 2) will be passed to Ronan’s model to trigger his venturi effect. Our group’s theme is Halloween so ‘Boiling Ice Land’ do give a steamy mysterious vibe to the whole RG machine.

Module Description

(i) Contraption introduction

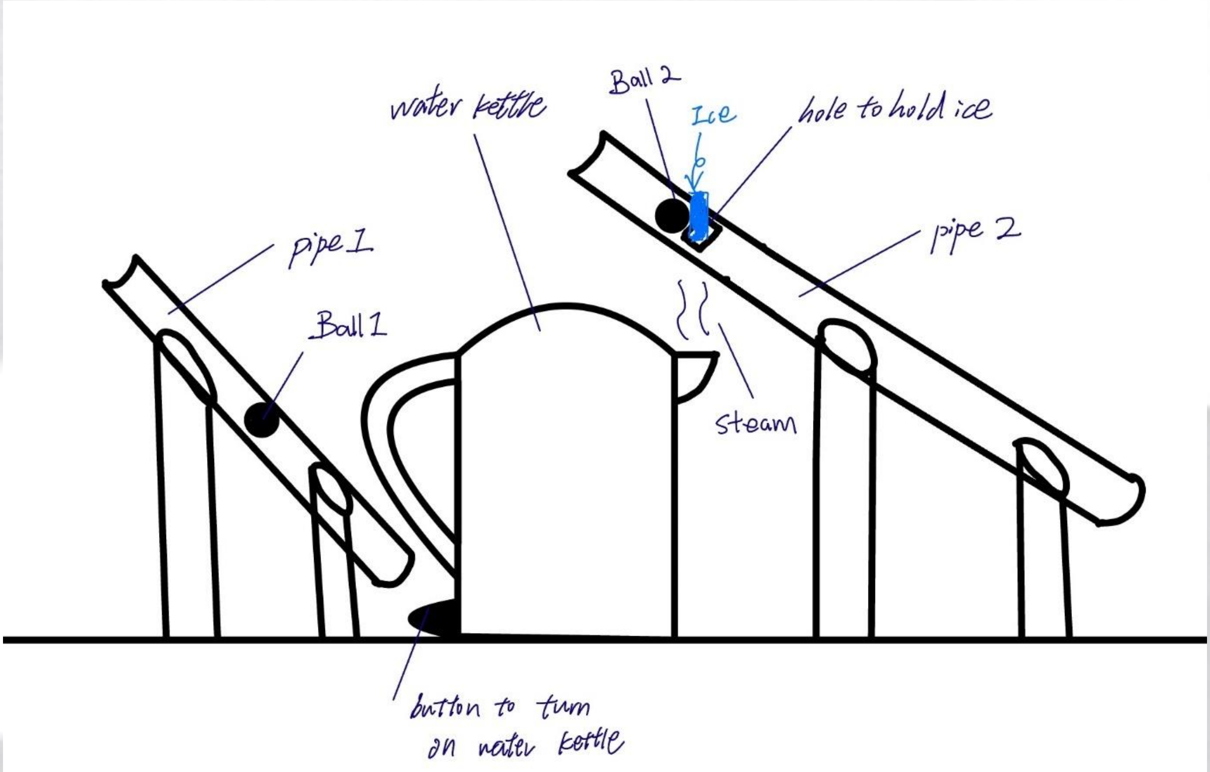

Image 1: The sketch of 'Boiling Ice Land'

Steps:

- An ice block is prepared before the experiment

1) Ball 1 from another model falls along pipe 1 and hits the button of the water kettle
2) Water boils and steam formed melt the ice
3) Ball 2 is placed and held behind the ice. Ice melts and the ball 2 falls along pipe 2

   Appendix 1 shows how the hole holds the ice.

Ball one comes from Isabel's module, and ball 2 is pushed to the Ronan's module, so "Boiling Ice Land" acts as the middle piece of our group's machine.

(i) Engineering Principle

In this model, energy is supplied to boil the water. By [$E_1 = mc\Delta T$], energy required for boiling water can be calculated from the mass, specific heat capacity and temperature change of water. At the same time, the concept of latent heat of vaporization [$E_2 = ml$] is included as water boil to form steam which acts as the medium to melt the ice.

For the ice, latent heat of fusion is used to calculate the energy required for melting the ice by $[E_3 = ml]$. It is assumed that the ice completely melts so ball 2 falls to simplify the calculation.

Thermal energy usage is crucial in chemical engineering field. From pharmaceutical to oil and petroleum industry, thermal energy usage takes place because heating is always a way to trigger reaction and release energy, etc. burning coal.

(i) Creativity

I think this model is creative because it shows how powerful water is. In this simple and compact model, the liquid, gas, and aqueous states of water are all shown. The coolest thing is that liquid water turns into gas state which force the solid water melt, there are no any new elements include, but just water itself changing its state to transfer the ball.

(i) Challenges

Steam has a high potential energy, but it still takes time to melt an ice block. “The model needs to be entertaining, so you need to think on the audience’s side and keep their focus on it.” Joseph Herscher said. [1]This reminds me of the point that is it possible to melt an ice block completely in the model. Therefore, I designed to cut a hole on pipe 2 which just perfectly hold the ice cube. When the ice slightly melts my steam, it becomes smaller and slip through the gap and falls, so ball 2 can flow down. This can greatly reduce time required for melting the ice and hence a more suitable model to be part of the RG machine.

For time management, the volume of water used in water kettle is also a struggling point. The smaller the volume of water used, the faster it boils and become steam. However, the smaller the volume of water used, the less steam available which may be insufficient to melt the ice. Therefore, I experimented with different volumes of water to find out the most suitable balance between the time to boil and amount of steam formed. The result was to use 150 cm^3 of water which gave the best balance of time and steam formed.

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[1] Video by Joseph Herscher https://media.ed.ac.uk/media/1_9vp8e6mc

Calculations

Part 1: Dimension Analysis by Buckingham Theorem

Table 1: Physical quantities and their dimensions

Physical Quantity	Symbol	Dimension
Specific heat capacity	c	$L^2T^{-2}K^{-1}$
Latent heat of vaporization/ fusion	l	L^2T^{-2}
Mass of water	m	M
Time	t	T
Temperature change	T	K
Density of water	p	ML^{-3}
Surface area of ice block	A	L^2

$f\,(c, l, m, t, T, A, p) = 0$

$\Pi = c^a\, l^b\, m^c\, t^d\, T^e\, A^f\, p^g$

$= (L^2T^{-2}K^{-1})^a \times (L^2T^{-2})^b \times M^c \times T^d \times K^e \times (L^2)^f \times (ML^{-3})^g$

$N_p = 7 \quad N_D = 4$

$N_p - N_D = 3$

Set c ,m , t as core variables.

L) $2a + 2b + 2f - 3g = 0$ ---- (1)

M) $c + g = 0$ ------------------- (2)

T) $-2a - 2b + d = 0$ ----------- (3)

K) $-a + e = 0$ ------------------ (4)

Case 1: a=1, c=0, d=0

From (2) : $0 + g = 0 \longrightarrow g = 0$

From (4) : $-1 + e = 0 \longrightarrow e = 1$

From (3) : $-2(1) - 2(b) + 0 = 0 \longrightarrow b = -1$

From (1) : $2(1) + 2(-1) + 2(f) - 3(0) = 0 \longrightarrow f = 0$

$\Pi_1 = \frac{cT}{l}$

The simplified physical meaning of this dimensionless group is time required for boiling water and melt the ice.

Case 2: a=0, c=1, d=0

From (2) : $1 + g = 0 \longrightarrow g = -1$

From (4) : $-0 + e = 0 \longrightarrow e = 0$

From (3) : $-2(0) - 2(b) + 0 = 0 \longrightarrow b = 0$

From (1) : $2(0) + 2(0) + 2(f) - 3(-1) = 0 \longrightarrow f = -\frac{3}{2}$

$\Pi_2 = \frac{m}{A^{\frac{3}{2}} P}$

The simplified physical meaning of this dimensionless group is the relationship between mass and surface area of the ice block, how mass of the ice change with surface area of the ice. In my module I want to minimize the mass and maximize the surface area of the ice to reduce time required for boiling.

Case 3: a=0, c=0, d=1

From (2) : 0 + g = 0 $\longrightarrow$ g = 0

From (4) : -0 + e = 0 $\longrightarrow$ e = 0

From (3) : -2(0) -2(b) + 1 = 0 $\longrightarrow$ b = $\frac{1}{2}$

From (1) : 2(0) + 2($\frac{1}{2}$) +2(f) + 3(0) = 0 $\longrightarrow$ f = $-\frac{1}{2}$

$\Pi_3 = \frac{\sqrt{l}t}{\sqrt{A}}$

The simplified physical meaning of this dimensionless group is that time is inversely proportional to the square root of surface area of ice. This interprets that time is inversely proportional to length of ice as $\sqrt{A} = \sqrt{L^2} = L$. The longer the length of ice with constant mass, the greater the surface area and hence the less time required to melt the ice.

Part 2: Dynamic scaling

The above model shows the heating and cooling in a precise and small model. However, in real life, these processes are often spread throughout a long reaction route. For example, a power station. A power station is usually built near the sea[2], it is important because seawater acts as a cooling agent to cool down hot water produced, otherwise the industry will explode and put people in danger when the plant is in an extremely high temperature. At the same time, these industries need sea water for reaction, however using salty sea water directly will damage gears and structures in the power plant, so there will be thermal desalination process[3]. This is to evaporate water and subsequently condense it again which requires heating process. In the following I will try to scale up my model by applying dynamic scaling using the dimensionless groups calculated in part 1.

In the above scaled-up model assume surface area of water to be heated up equals 5π m^2

Table 2: Values for each physical quantities in BIL [4]and scaled-up model

Physical quantities	Symbol	Dimension	Values of 'Boiling Ice Land'	Value scaled up to industrial usage
Specific Heat Capacity	c	$L^2T^{-2}K^{-1}$	4200 J kg^{-1} °C^{-1}	4200 J kg^{-1} °C^{-1}

[2] Why power stations are built near the sea? Why do power stations need to be near water? – TeachersCollegesj
[3] Thermal desalination process, Thermal Desalination - an overview | ScienceDirect Topics
[4] BIL = Boiling Ice Land

Latent Heat of Vaporization/ Fusion	l	L^2T^{-2}	3.36×10^5 J kg^{-1} 2.26×10^6 J kg^{-1}	3.36×10^5 J kg^{-1} 2.26×10^6 J kg^{-1}
Mass of water	m	M	0.4 kg	(to be calculated)
Time	t	T	63.78 s	(to be calculated)
Temperature change	T	K	82℃	82℃
Density of water	p	ML^{-3}	1000 kg m^{-3}	1000 kg m^{-3}
Surface area of ice block	A	L^2	$0.0016\,\pi$ m^2	$5\,\pi$ m^2

Consider Π_2 and Π_3,

$(\frac{m}{A^{\frac{3}{2}}P})_{BIL} = (\frac{m}{A^{\frac{3}{2}}P})_{I}$ [5] ----- (1)

$\left(\frac{\sqrt{l}t}{\sqrt{A}}\right)_{BIL} = \left(\frac{\sqrt{l}t}{\sqrt{A}}\right)_{I}$ ------ (2)

From (1), mass of water can be found

Substitute values from the above table into formula (1):

$$\frac{0.4}{(0.0016\,\pi)^{\frac{3}{2}}} = \frac{m}{(5\,\pi)^{\frac{3}{2}}}$$

m = 69900 kg

From (2), time for boiling water can be found:

$\left(\frac{63.78}{\sqrt{0.0016\,\pi}}\right) = \left(\frac{t}{\sqrt{5\,\pi}}\right)$

t = 3570 s

Part 3: Error propagation and uncertainties

In the following, the relationship *t* (time to boil water) is linearly proportional to *m* (mass of water in water kettle) is proved, under the 4 assumptions to simplify the calculations:

1) The tap water used was assumed to be pure water without considering effects of impurities in water that may affect the experiment.
2) *c* (the specific heat capacity) and *p* (density) of tap water was assumed to remains constant.
3) ΔT (Temperature change) between tap water and boiled water was assumed to remains constant.

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[5] I = Industrial model, which is the scaled-up model

4) The W (power) supplied to the water kettle was assumed to remain constant.

Precautions in carrying the experiment:

1) Ensure the water kettle is cooled before next boiling, this can prevent heat left in the kettle that led to reduced time recorded for boiling.
2) Wrap the kettle with towel to minimize heat loss to surroundings which may cause a longer time for water to boil.

(i) Considering the error of mass

By mass = density x volume, where density of water is assumed to be constant. Mass is proportional to volume. Therefore, by deriving errors in measuring volume of water, the error in measuring mass of water can be obtained.

By $\boldsymbol{V = \bar{V} \pm \delta V}$, where $\boldsymbol{V}$ is the mean and $\boldsymbol{\delta V}$ is the absolute error on this parameter.

By using a water bottle as my instrument for measuring the volume of water, the scale of instrument of measure is 100 ml. The uncertainty associated with time is half the scale of instrument of measure which is 50 ml. However, the uncertainty seems too high which doesn't make sense. It is acknowledged that relative error smaller than 10% is a reasonable one in most of the experiment. Therefore, after possible estimation and consideration, the uncertainty is set to be 5 ml. Take volume measures as 100 ml in this case, this gives ***V= 100 ± 5 ml,*** and the relative error will be $\frac{\delta V}{\bar{V}} = \frac{5}{100} = 0.05 = 5\%$

As 1 ml = 1 g etc., **V** in the following is written as **m**

Therefore, the estimated mass of water in water kettle is ***m = 100 ± 5 g***

which is ***m = 0.1 ± 0.005 kg*** in S.I. units

However, the repeating measurement of same amount of water is difficult as precise measuring cylinder is needed and water leave on the wall of one container cannot be fully transferred, these lead to errors that are too small to be observed in this experiment.

(ii) Considering the error of time measured

By $\boldsymbol{t = \bar{t} \pm \delta t}$, where $\boldsymbol{t}$ is the mean and $\boldsymbol{\delta t}$ is the absolute error on this parameter.

I use my smartphone's timer to take the measurement which has the smallest scale of 00:00:01, which is 0.01 seconds. Half the scale of the instrument of measure will give 5 x 10^{-3} seconds which is impossible as it is extremely smaller than human reaction time, which is the major reason behind the time measurement error. Therefore, in this case I used the range method to measure the time.

Take the time for boiling 100 ml of water as an example, t_1, t_2 and t_3 are the three results measured for boiling 100ml of water

t_1= 20.23 s t_2 = 23.34 s t_3 = 21.42 s

$\delta t_{,range} = \frac{t_{max}-t_{min}}{n} = \frac{23.34-20.23}{3} = 1.04\ s$

$\bar{t} = \frac{20.23+23.34+21.42}{3} = 21.66\ s$

$(\frac{\delta t}{t})_{range} = \frac{1.04}{21.66} = 0.0480 = 4.80\ \%$

Therefore, the time for boiling 100 ml of water can be approximated as ***t* = 21.66 ± 1.04 *s***

Therefore, the time for boiling n ml of water can be approximated as $\boldsymbol{t_n = \bar{t}_n \pm (\bar{t}_n \times 0.0480)\ s}$

The Graph 1 sketched below with a best-fitted line with intercept fixed at (0,0), and the line shows a very similar linear trend with the scatters plotted. This proofs the linear relationship of $t = k\ m$, where k = $\frac{c\Delta T}{W}$.

$$E = mc\Delta T$$

$$tW = mc\Delta T$$

$$t = \frac{mc\Delta T}{W}$$

E is the energy required to boil water, $W, \Delta T$, *c* are constant in the equation and are highlighted, leaving *t and m* unhighlighted. So, *t* is linearly proportional to *m.*

Slight deviations of scatters with the best-fitted line are due to the **following possible experimental errors:**

1) Heat loss to surrounding during heating, which increase the time for boiling same volume of water.
2) The measurement scale of the cup is not accurate and precise[6], leading to slight difference in volume of water measured
3) Human error in time measurement, etc. not turning on the water kettle and start timing at the same time.

[6] Error in measuring apparatus Measuring Cylinder/Graduated Cylinder Definition Uses Functions - All You Need to Know Before Using or Buying! | Laboratory Apparatus,Science Lab Equipment,Teaching Materials,Lab Supplies Manufacturer,Supplier & Exporter - https://laboratory-apparatus.com

1) *Refer to Table 3 in (*Appendix 1:

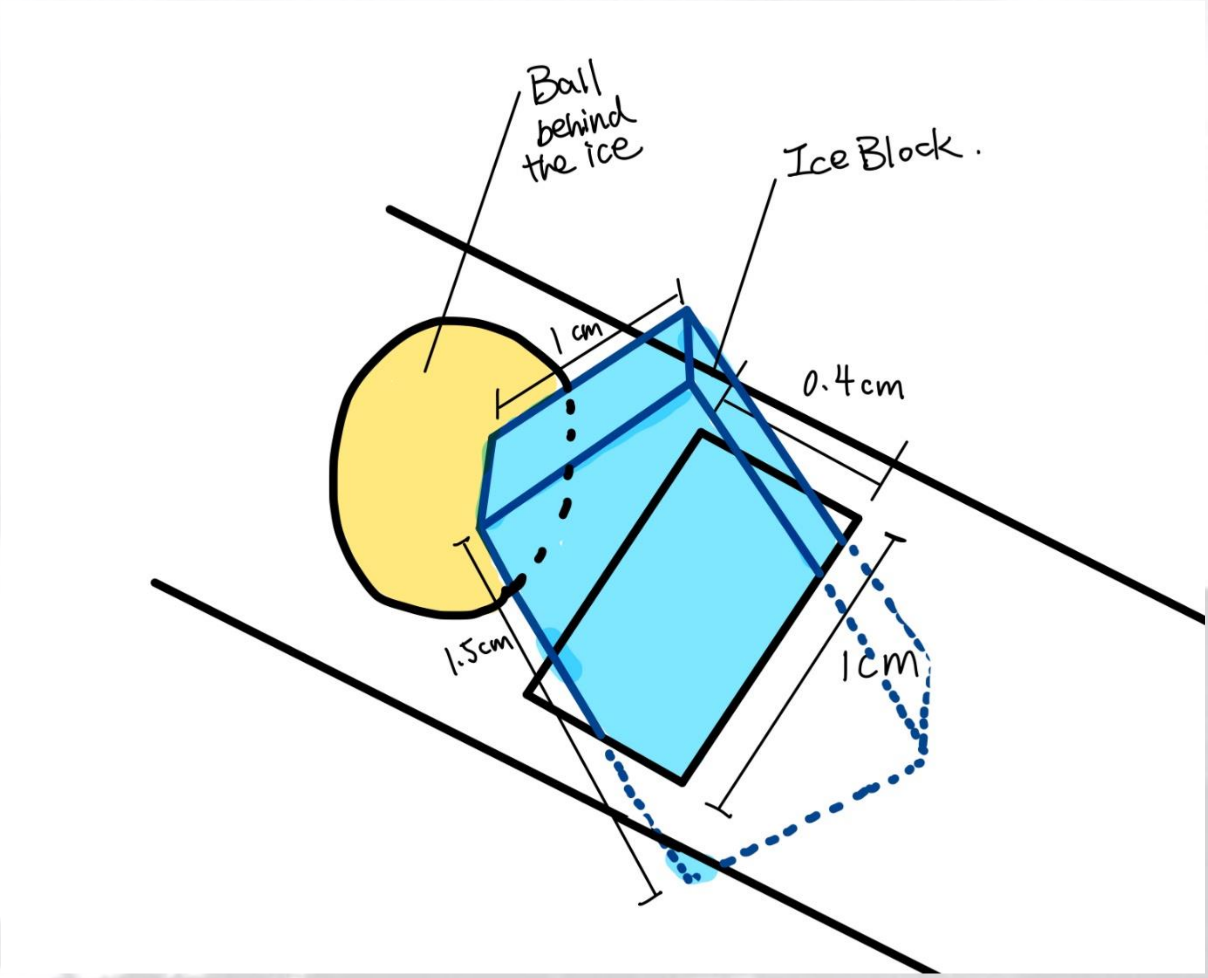


Image 2: A close-up sketch to the hole that holds the ice block

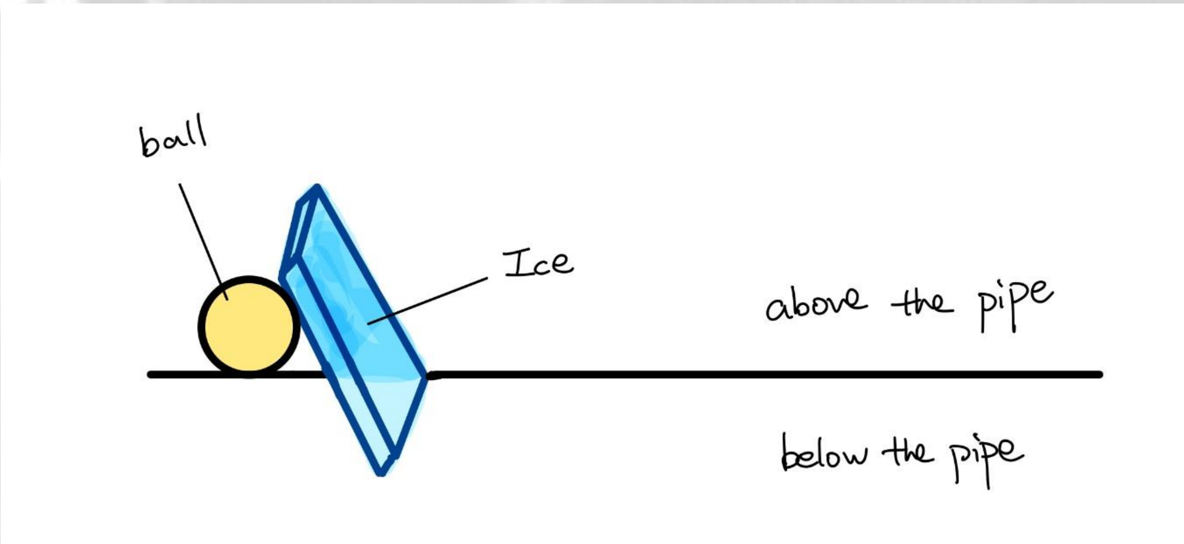
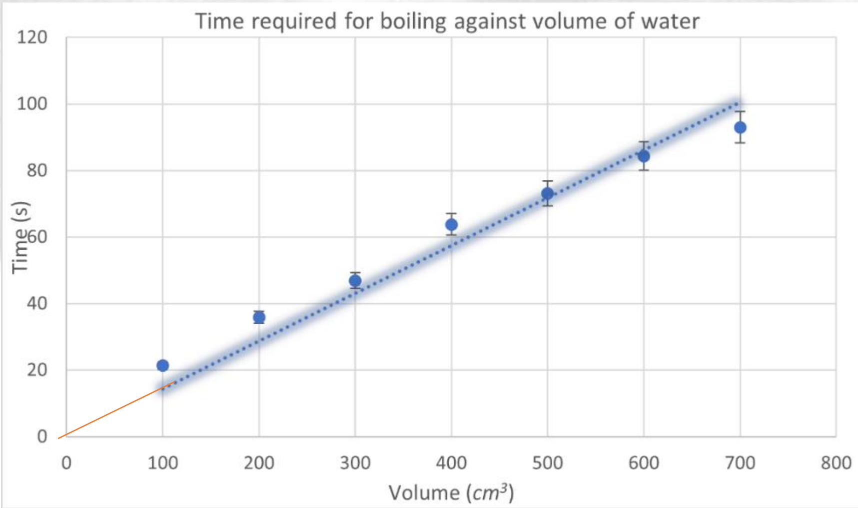


Image 3: Side-view of the close-up sketch to the hole that holds the ice block

Appendix 2 : Table 3 for experimental results collected) *for the experimental results collected from boiling different volumes of water*.

Graph 1: Time required for boiling against volume of water



Reflection:

When it comes to the final stop of the project, I am very happy and glad to have worked with my groupmates and excited to see the final video of combining all our modules together. Our group worked in a relax and open-minded ambience, we were not hesitated to make changes to our own module after listening to other's idea. However, compared to my experience in Reflective Engineer 1 project, we were shy to share ideas to more people in a group, and behaving so embarrassing when meeting each other, this had slowed down our working path on this project. If I were facing the same issue in my next project, I would try to lead the group and take the initiative to ask groupmates who are less engaged with more questions, trying to get them together into the discussion. I believe this could bring all of us closer and build our team spirit, so everyone would be happy to share their ideas more and hence creating something bigger and greater together.

Regarding my own independent work, my report's organization and planning has improved compared to my last project. However, I am trying to put everything into a report which may make it less concise and lost its focus. If I were doing my next project, I need to improve my ability in including important information and sacrifice those which are not super relevant to the project.

References

1) "The model needs to be entertaining, so you need to think on the audience's side and keep their focus on it." , Joseph Herscher, 1.Personal story https://media.ed.ac.uk/media/1_9vp8e6mc

2) Why are power plants built near the sea?, Teacherscollegesj, Why do power stations need to be near water? – TeachersCollegesj

3) Thermal desalination process, Science Direct, Thermal Desalination - an overview | ScienceDirect Topics

4) Errors in measuring apparatus, Htstar, Measuring Cylinder/Graduated Cylinder Definition Uses Functions - All You Need to Know Before Using or Buying! | Laboratory Apparatus,Science Lab Equipment,Teaching Materials,Lab Supplies Manufacturer,Supplier & Exporter - https://laboratory-apparatus.com

Appendix

2) Appendix 1:

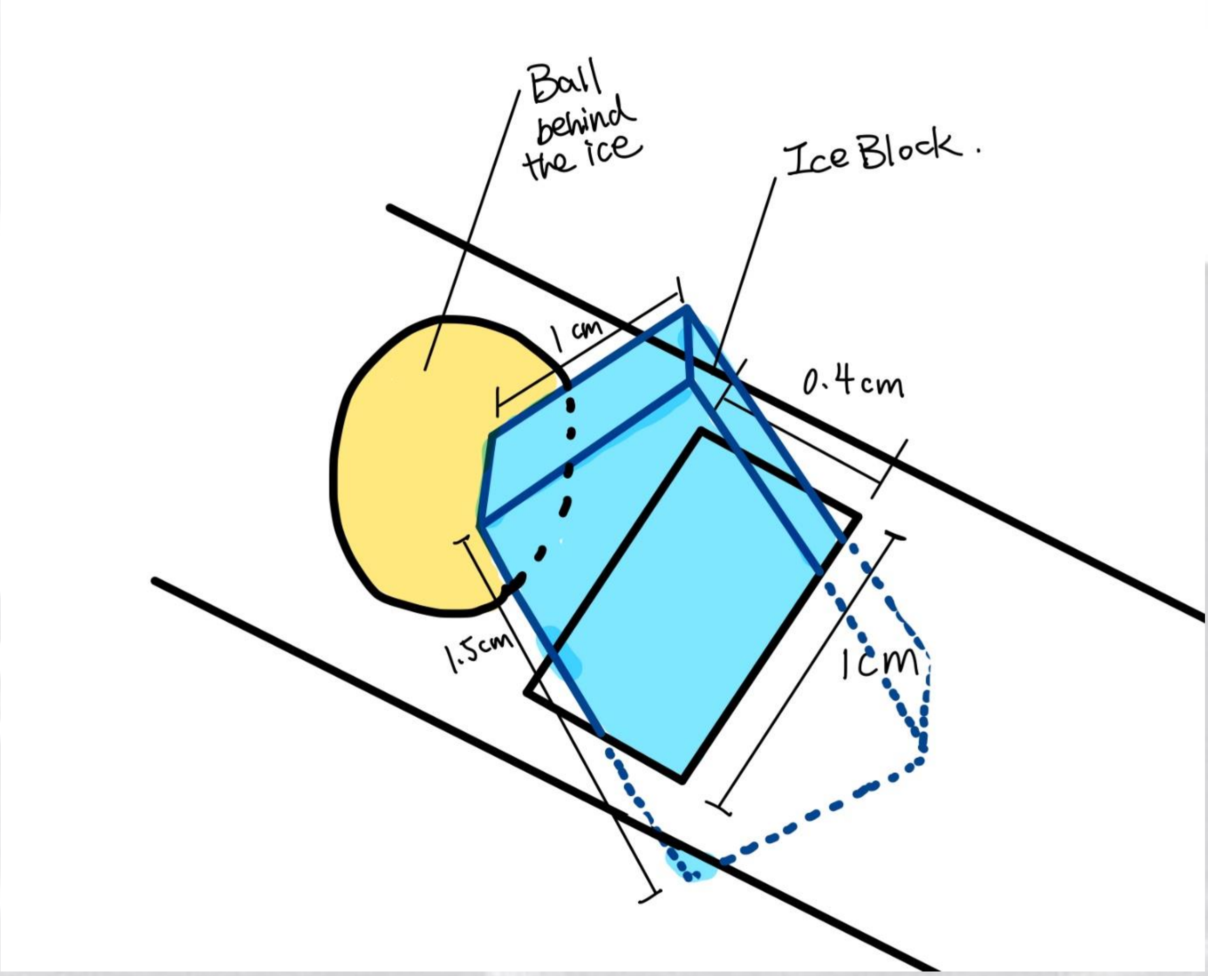


Image 2: A close-up sketch to the hole that holds the ice block

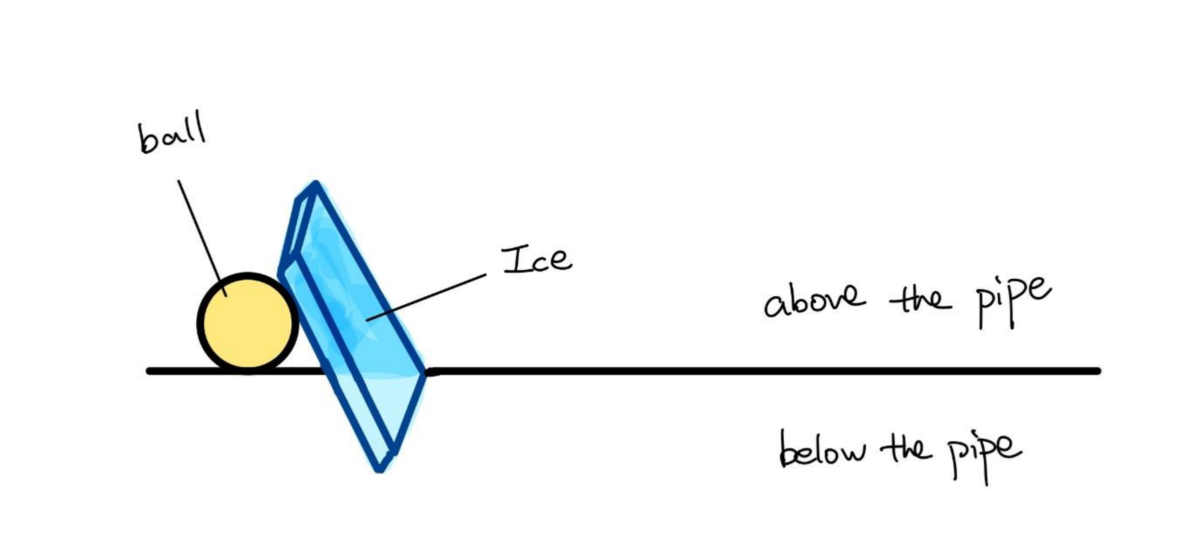


Image 3: Side-view of the close-up sketch to the hole that holds the ice block

3) Appendix 2 : Table 3 for experimental results collected

Table 3 : Results of time measured and approximated values with relative error considered

Mass (g)	***Time result set 1 (s)***	***Time result set 2 (s)***	***Time result set 3 (s)***	***Average of time measured (s)***	***Approximated value of time measured (s)***
100 ± 5	20.23	23.34	21.42	21.66	21.66 ± *1.04*
200 ± 5	35.69	37.22	34.67	35.86	35.86 ± *1.72*
300 ± 5	48.46	46.10	45.96	46.84	46.84 ± *2.25*
400 ± 5	63.55	65.33	62.47	63.78	63.78 ± *3.06*
500 ± 5	73.16	72.41	73.90	73.16	73.16 ± *3.51*
600 ± 5	85.66	82.76	84.58	84.33	84.33 ± *4.05*
700 ± 5	90.90	93.40	94.62	92.97	92.97 ± *4.46*

Risk Assessment for Individual Technical Report

Activity Location:	Kitchen	**Assessment Submitted By:**	Jasmine Lai
Task:	RGM project	**Date:**	02/11/2022

Hazards	Risk (Health & Safety)	Initial Level of Risk			Control Measures	Revised Level of Risk		
		H	M	L		H	M	L
Splash of water onto the heating base of water kettle	Short circuit		x		Wipe the water kettle before putting it onto the heating base.			x
Steam formation	Physical injury	x			Do not move the ice block or make further adjustments of the pipes after turning on the water kettle.			x
Crowed area with stove	Fire disaster		x		Ensure the electric cooktop is turned off before the experiment. Pipes are made from toilet paper cardboard core, which is flammable material, ensure pipes are stuck strongly on the wall to prevent them from falling.			x
Pouring hot water	Skin burn	x			Handle the hot water carefully and pour it slowly into the sink, this can prevent reflection of hot water from the sink which will cause skin burn.			x