Revisiting capillary rise experiments
Can evaporation limit it?

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Overview

1. Introduction
2. Previous works – Relation to cooling systems
3. Experimental setup
4. Results
5. Conclusions

Problem statements

Competition b/w evaporation and surface tension

Capillary rise / spreading in varying c/s area porous systems

Questions to be answered

Q1. **Horizontal Capillary** – *Will it spread till infinity*?

Q2. **Capillary length V/H porous medium** – *What limits it*?

Static parameters – Gravity / Viscosity / Capillary length

Dynamic parameter – Evaporation

Q3. **Exposed porous medium** – *Is evaporation a limiting parameter*?

Notable Works

Lucas (1918) & Washburn (1921) - *Lucas-Washburn* law - the distance penetrated by a liquid in an initially gas-filled lyophilic capillary tube placed horizontally.

$$h \propto t^{1/2}$$

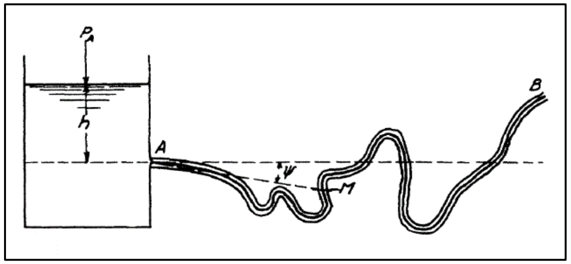
Levine (1980) – Quite complicated relation between the liquid penetration depth and time .

Ponomarenko (2011) - capillary rise in a corner.

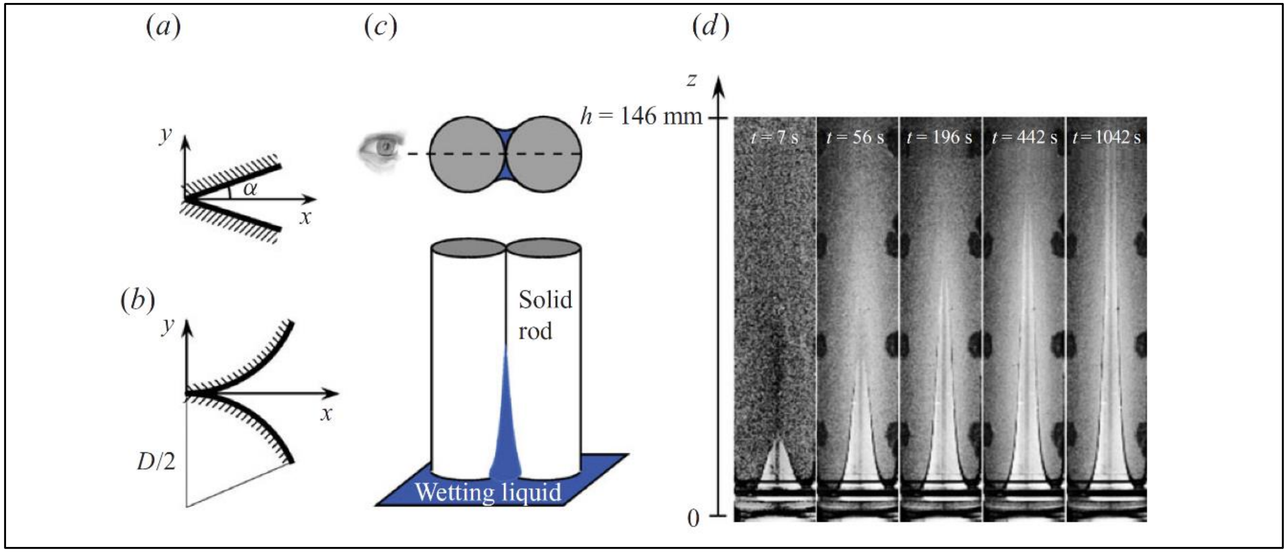
$$h \propto t^{1/3}$$

Vertical Corner

Horizontal Capillary



Washburn (1923)

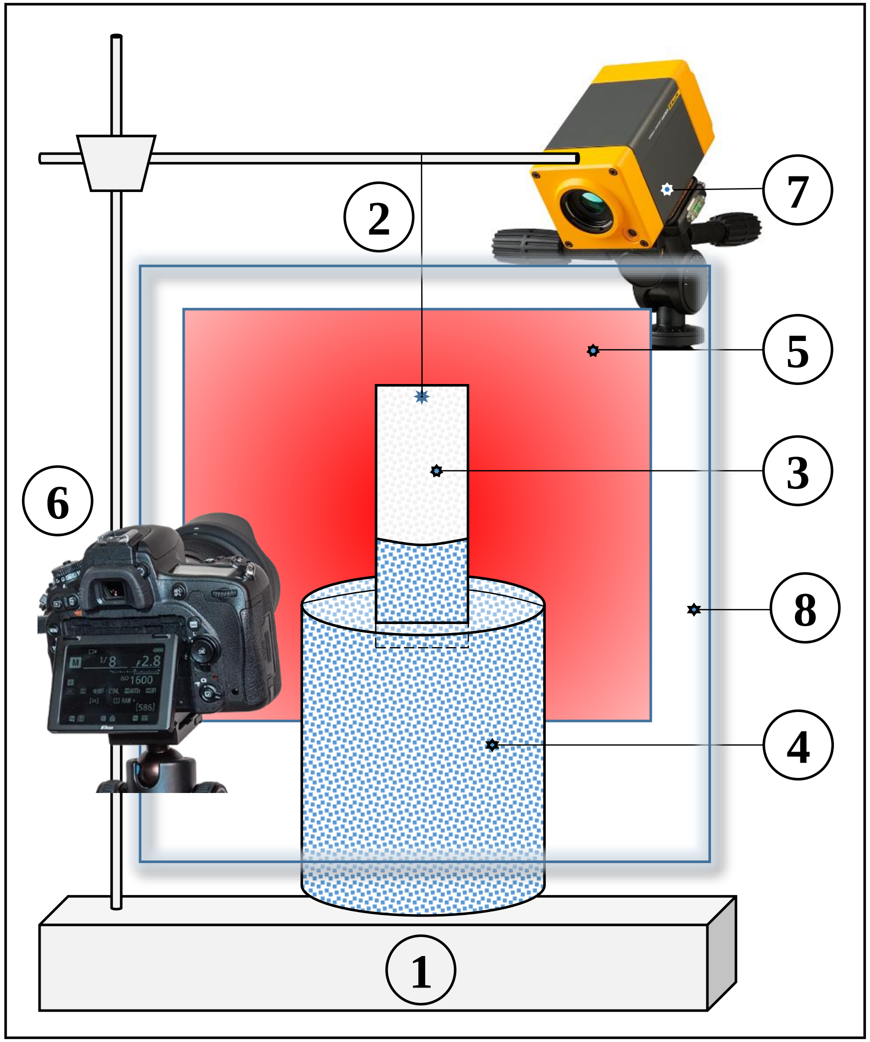


Ponomarenko (2011)

A filter paper – Complicated – Combination of capillaries and corners (joints of strands)

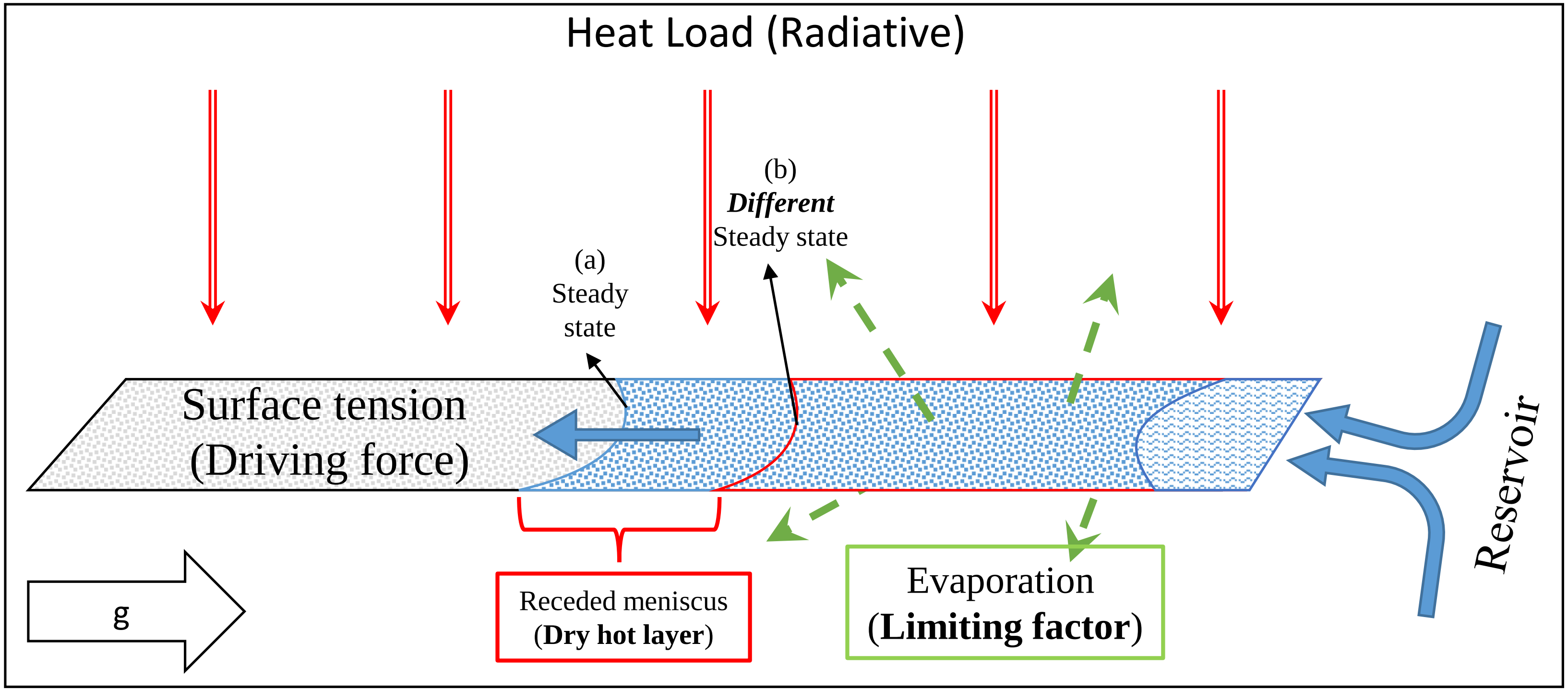
Experimental Setup & Method

1. Stand
2. Pin
3. Filter paper
4. Beaker
5. Heater
6. Optical Camera
7. Thermal Camera
8. Glass



Digital Image Processing
IR images & Videos
Full-scale data analysis

Mechanism



Drawbacks in case (b):

(a) Near-top high temperature

(b) Lower heat transfer to the interface

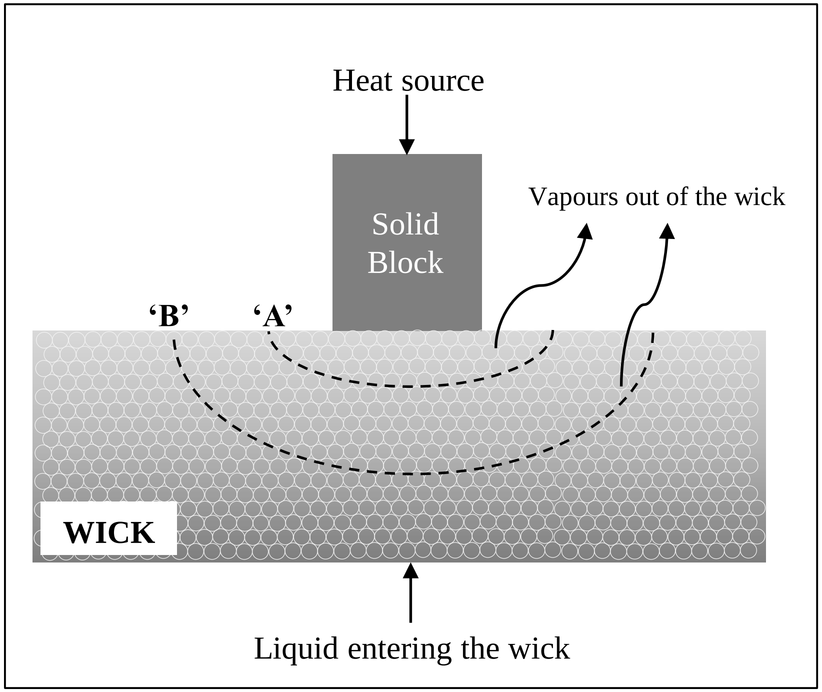
(c) Lower evaporation rate (cooling)

(d) Increased operating temperature

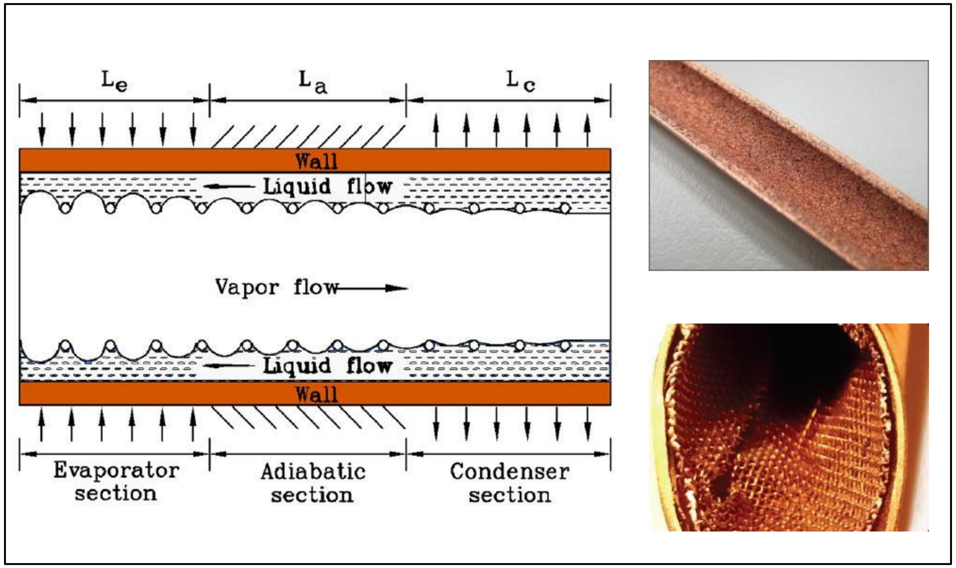
Competition between Sorption rate (surface tension) and vapour transformation rate (Evaporation) – Two Velocity Scales

Application – Heat pipe

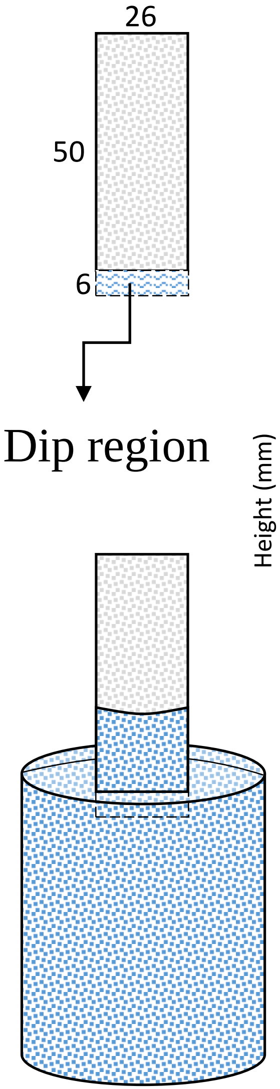
Kumar & Arakeri
(IJTS, 2020)

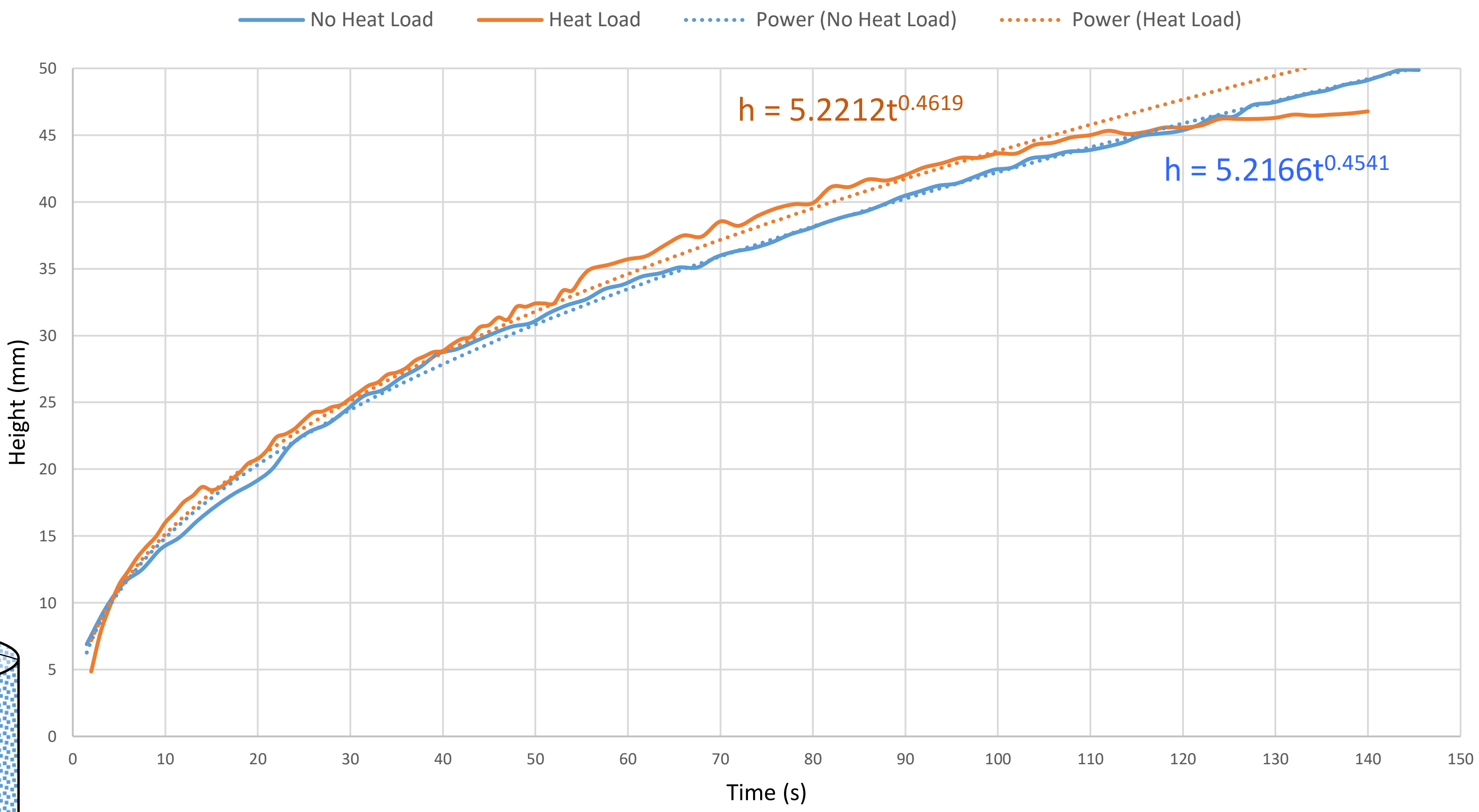


Faghri, 2005



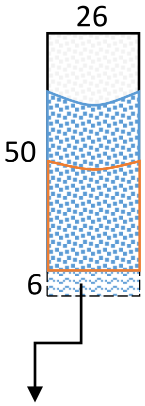
Results of Standard Liquid (Water)



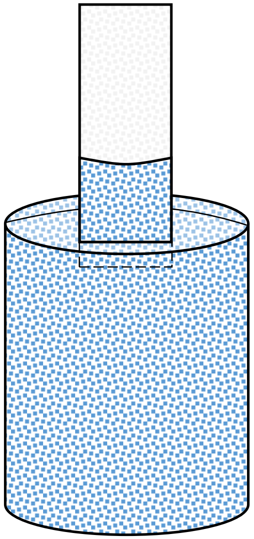


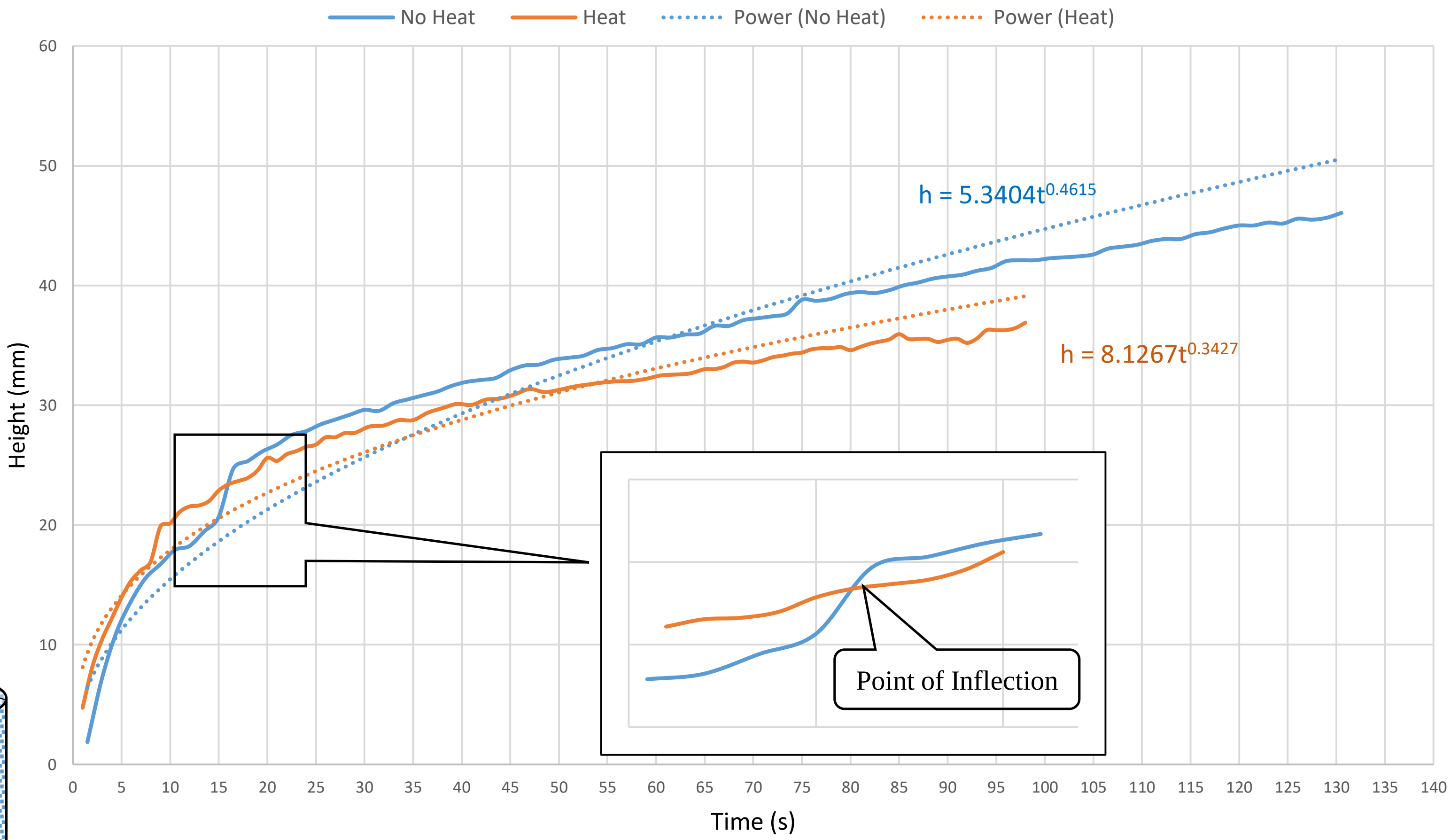
No significant effect of heat load is seen on the rise of water in any experimental configurations – The standard liquid.

Results of Volatile Liquid (Pentane)



Dip region

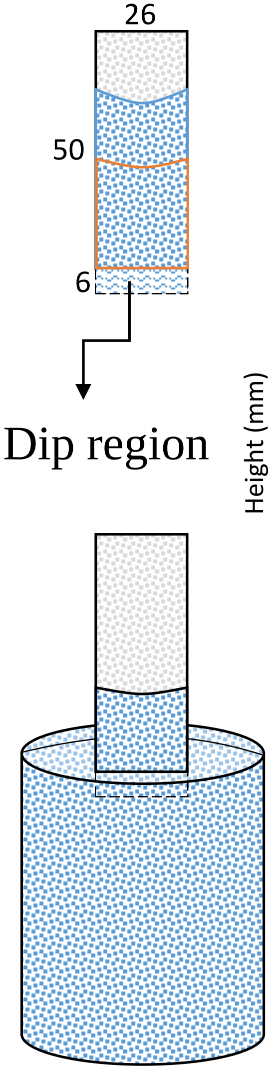


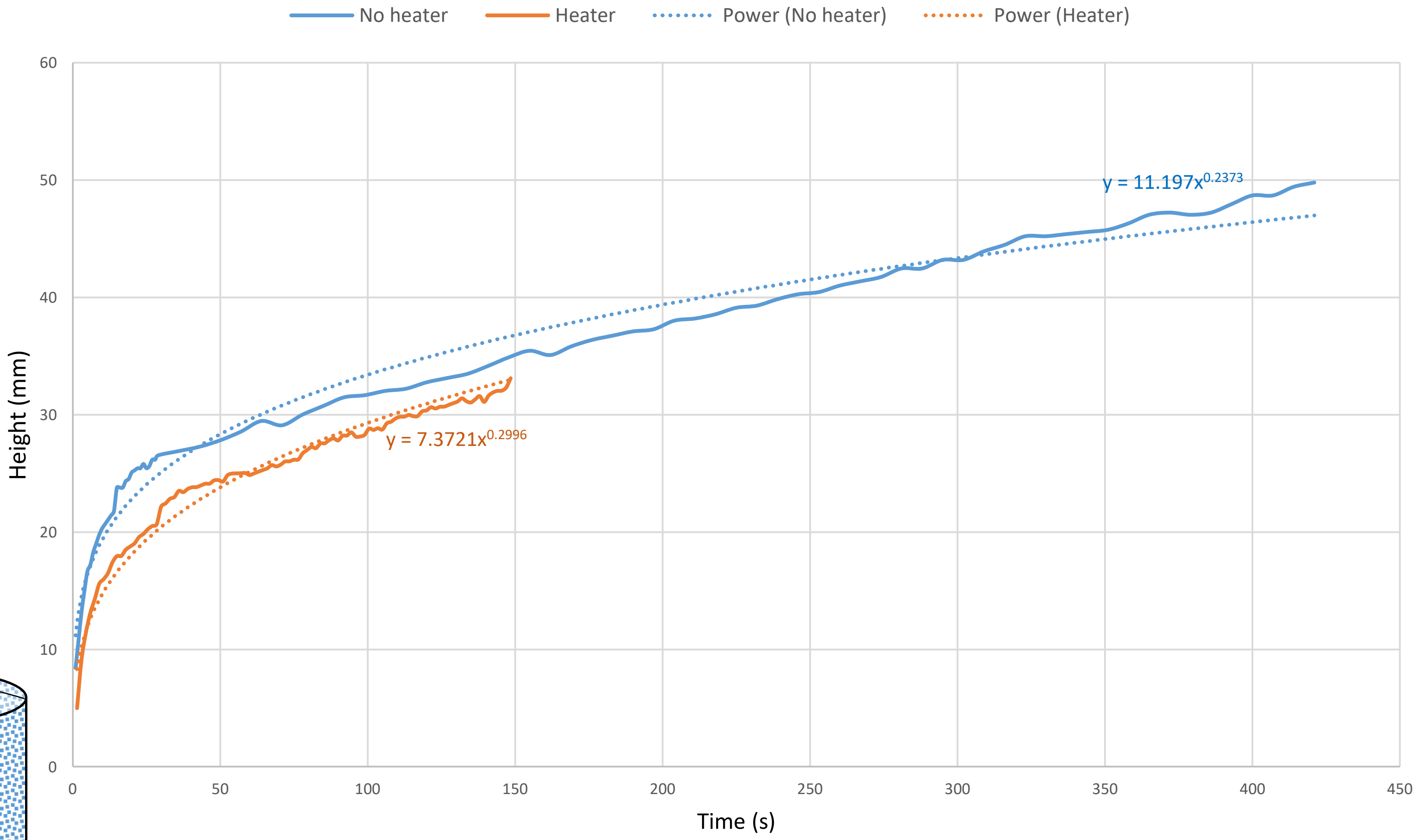


Less velocity
Higher height rise

High velocity
Lesser height rise

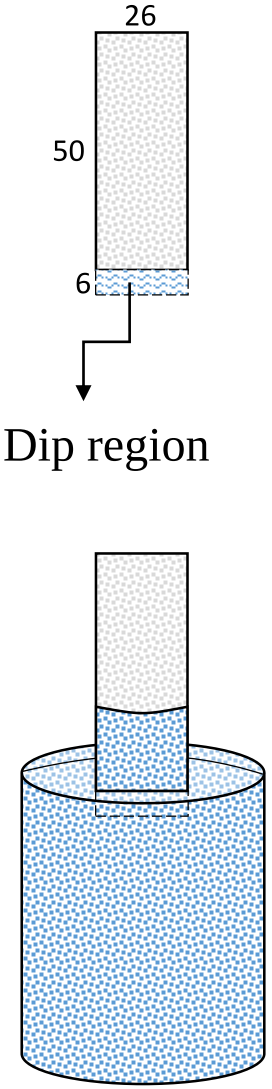
Results of Volatile Liquid (Acetone)

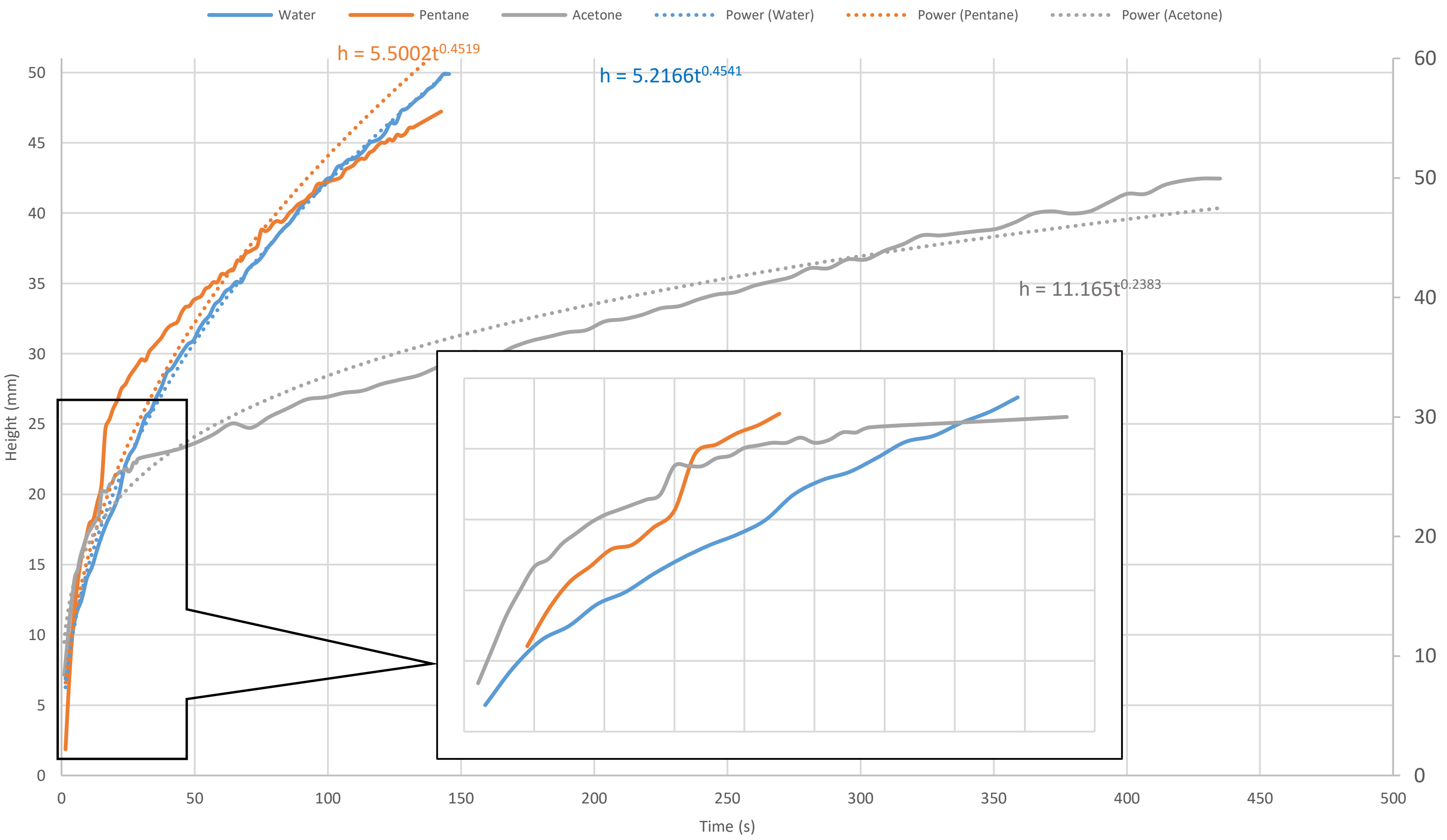




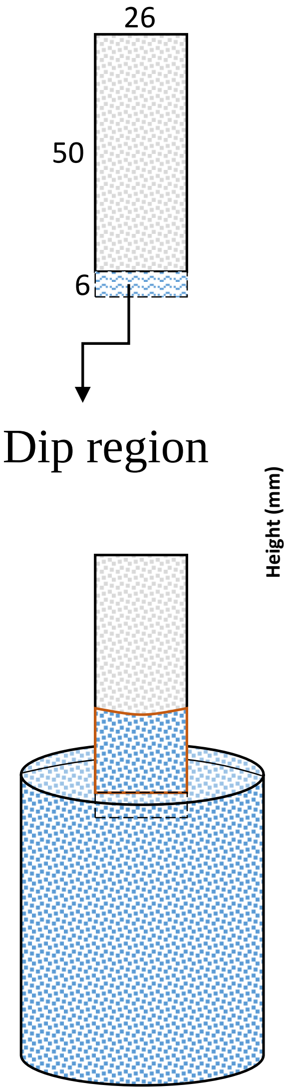
Hot acetone has low velocity and rises to lower heights

Comparison b/w Water, Pentane & Acetone (No Heat load)

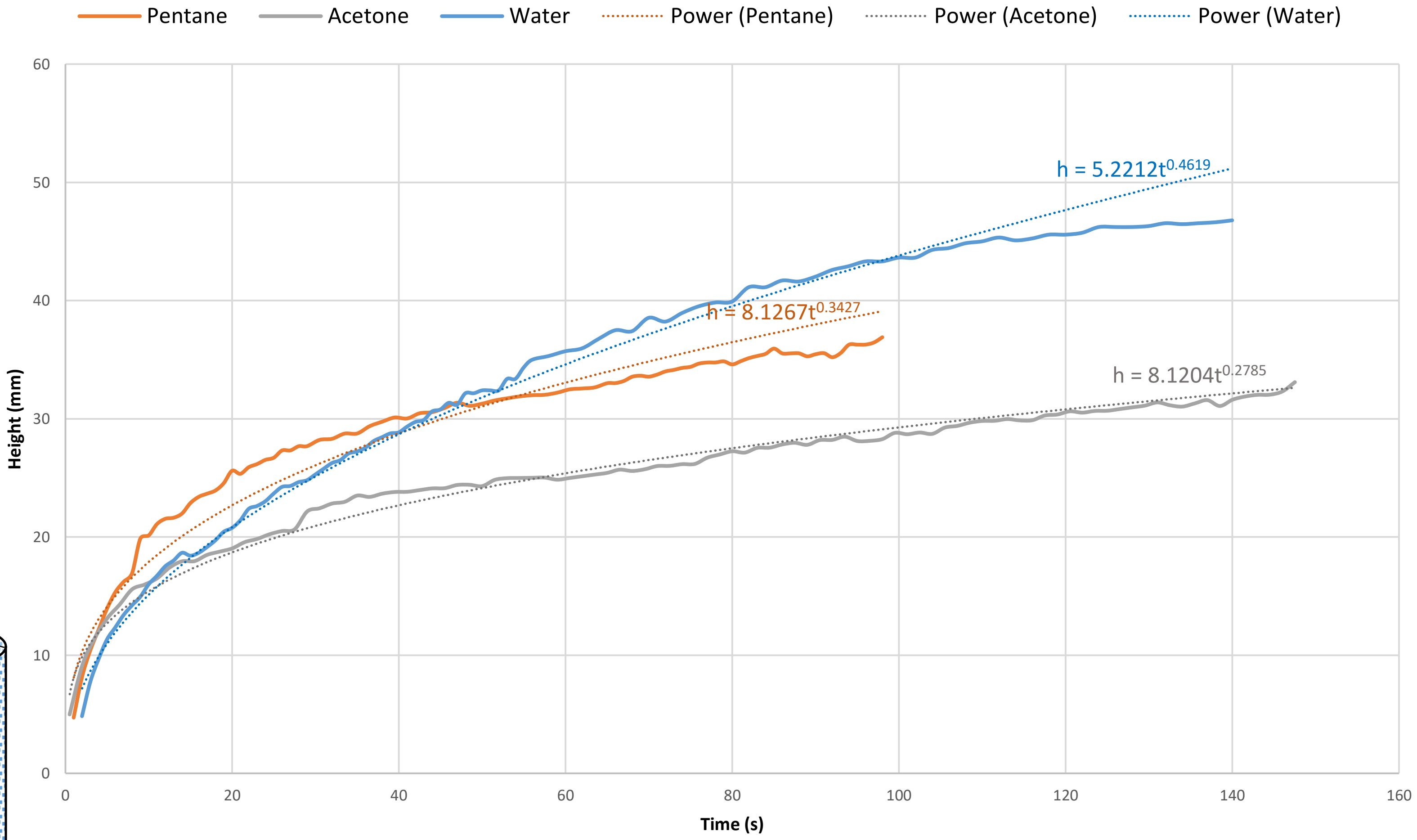




Comparison b/w Water, Pentane & Acetone (Heat load)



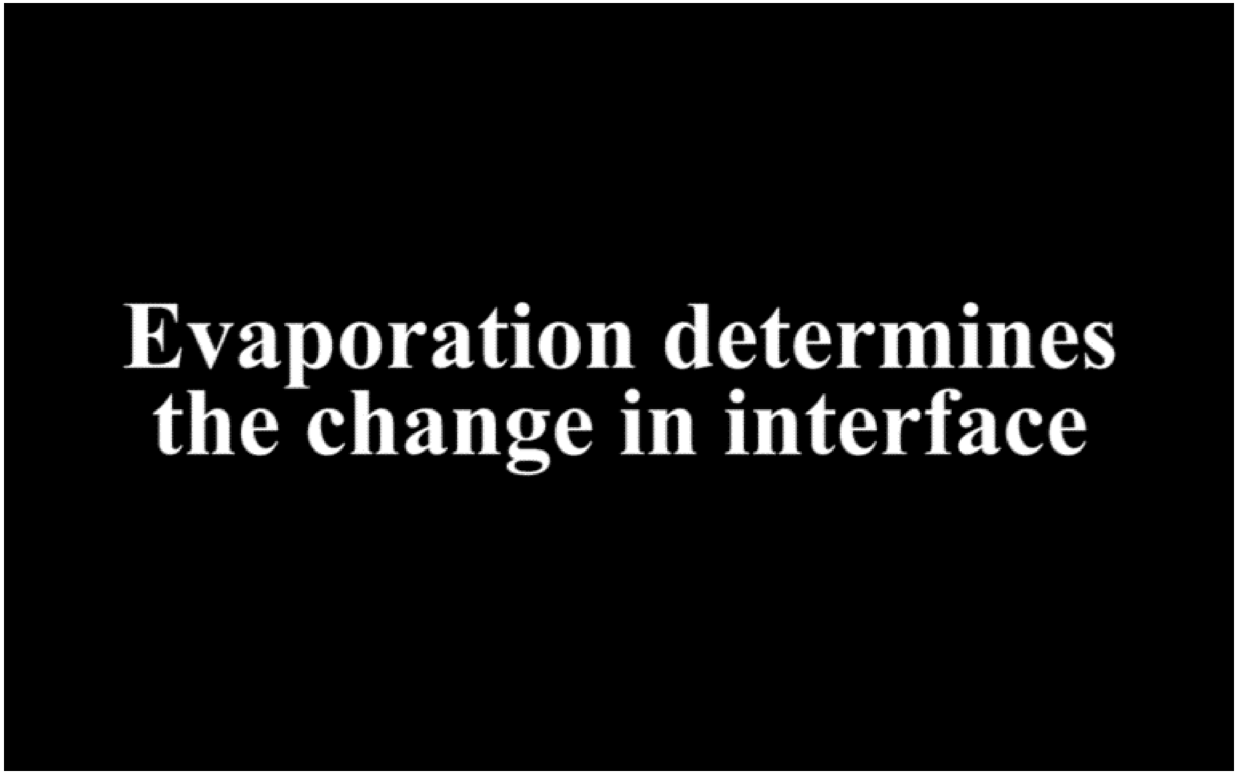
Dip region



Liquid height rise – increase in the order – Acetone < Pentane < Water

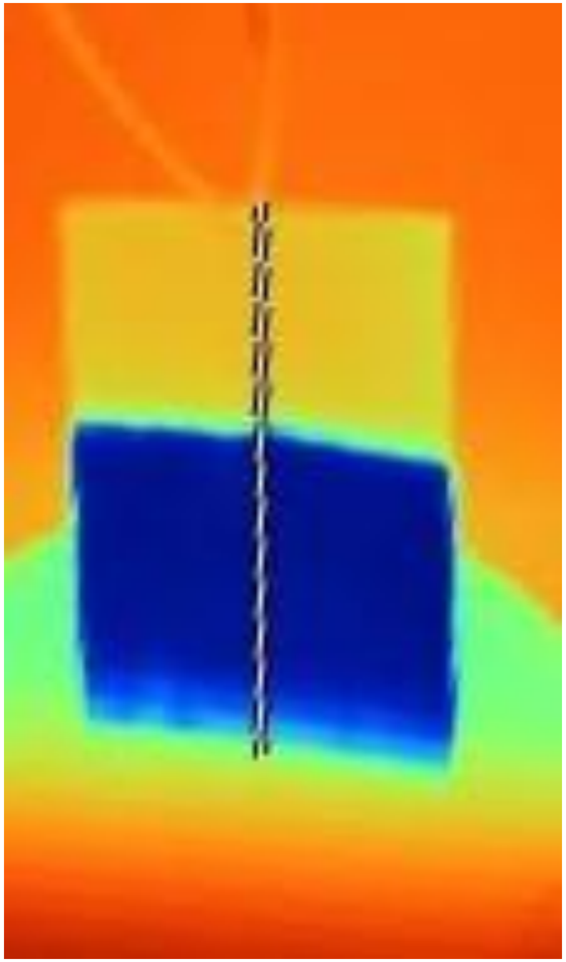
Results of Volatile Liquid on sudden removal of heat load (Pentane)

IR Video

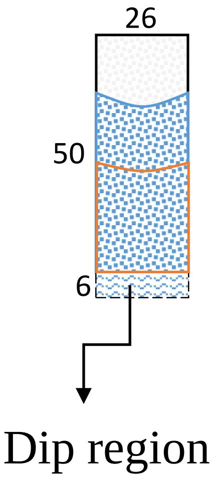


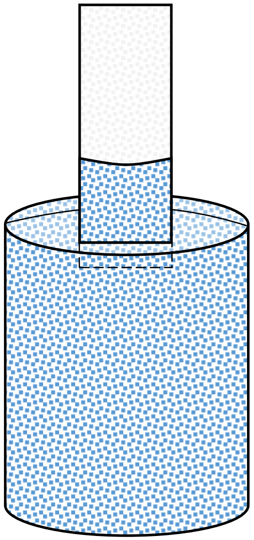
Evaporation determines the change in interface

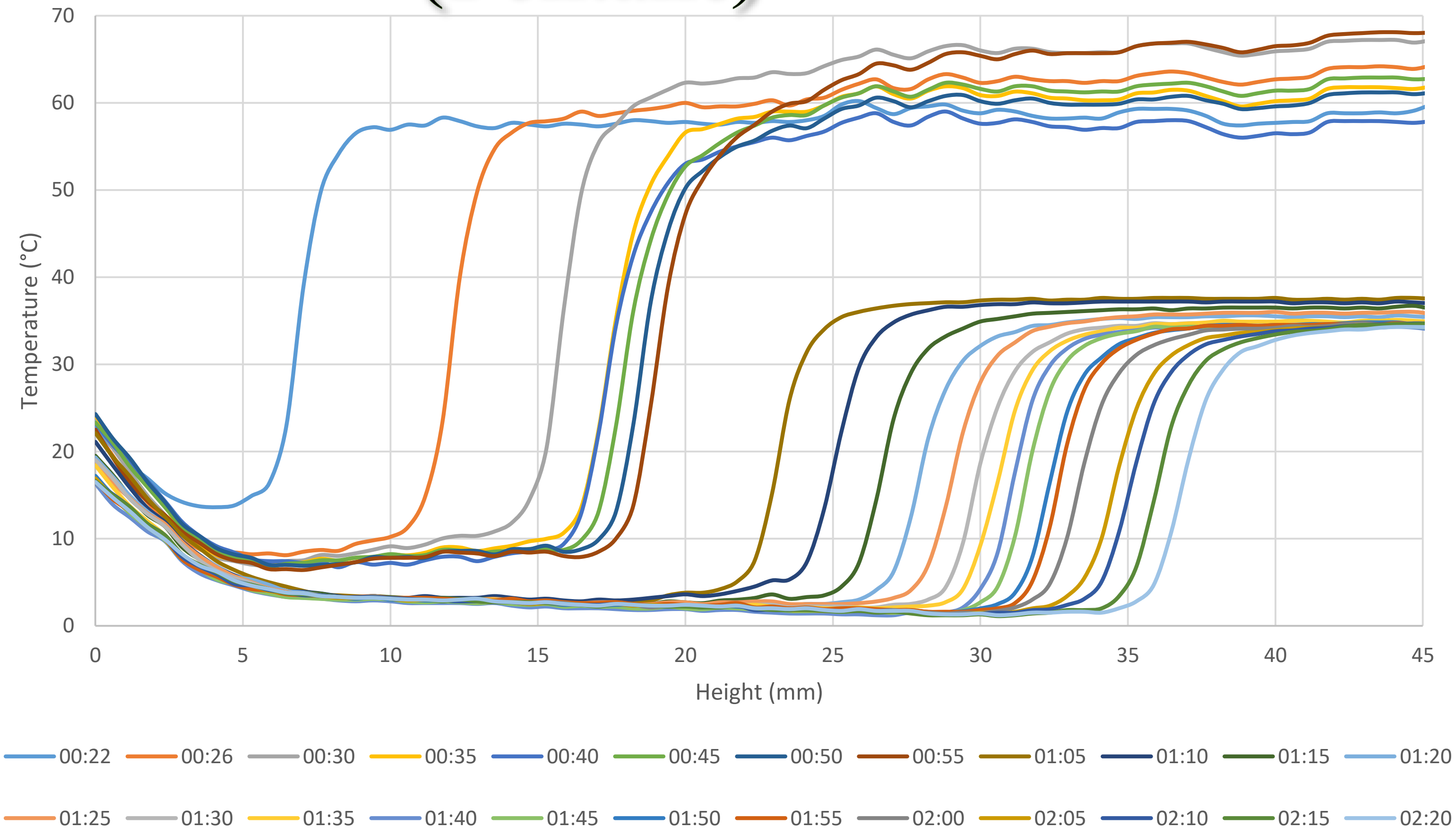
IR Image



Results of Volatile Liquid on sudden removal of heat load (Pentane)

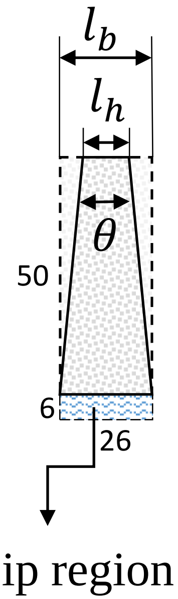




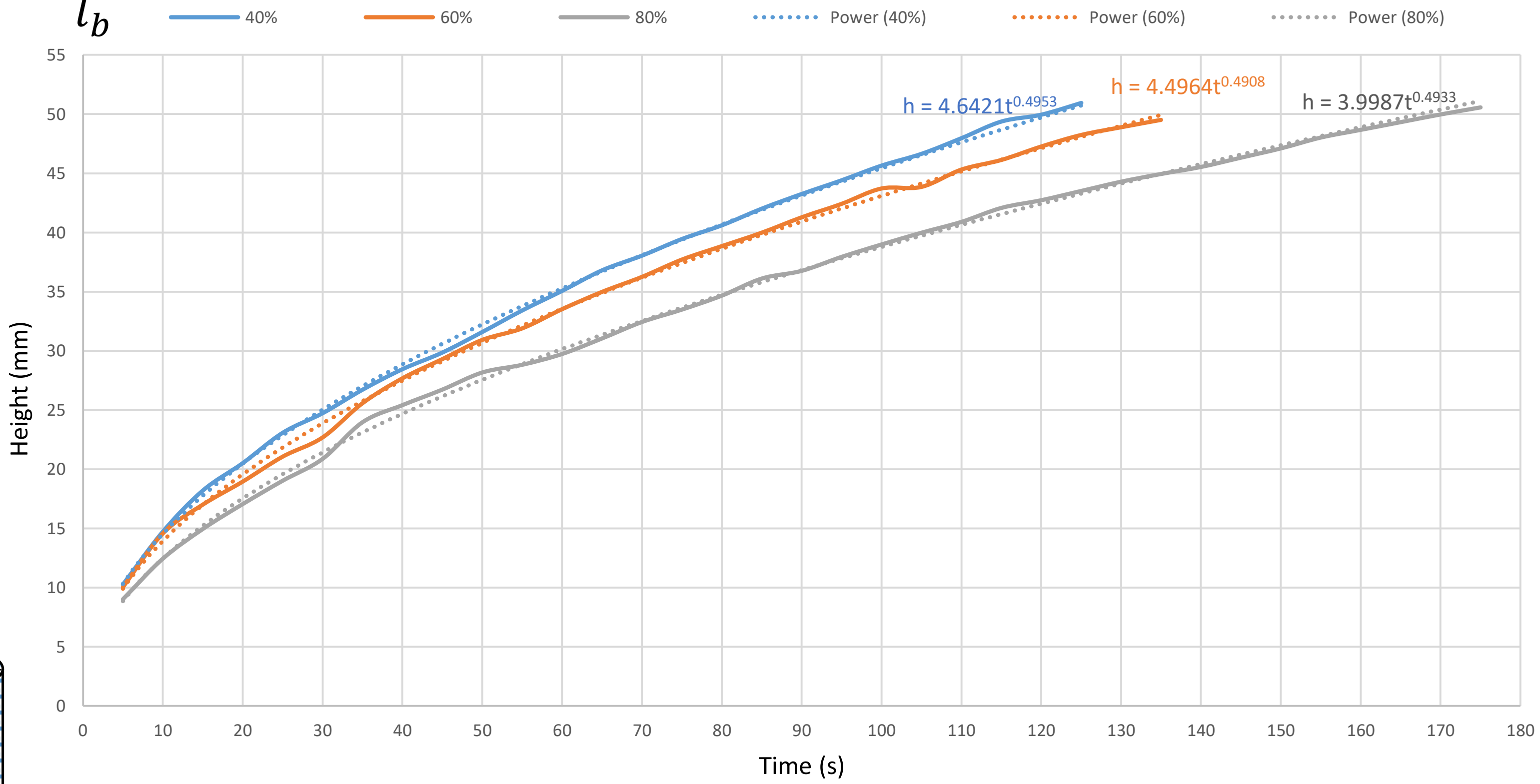


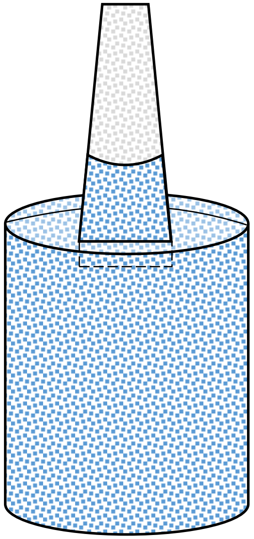
Increase in height – Removal of heat load

Results of Standard Liquid (Water) – Trapezium



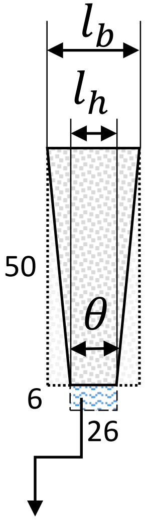
$$\% = \frac{l_h}{l_b} \times 100$$



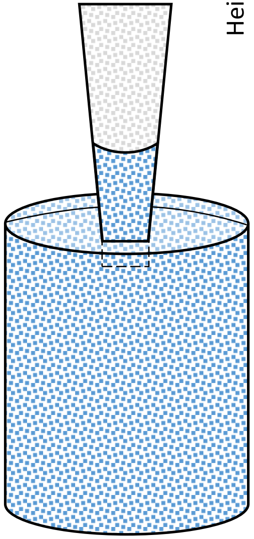


t ↓ with ↑ θ

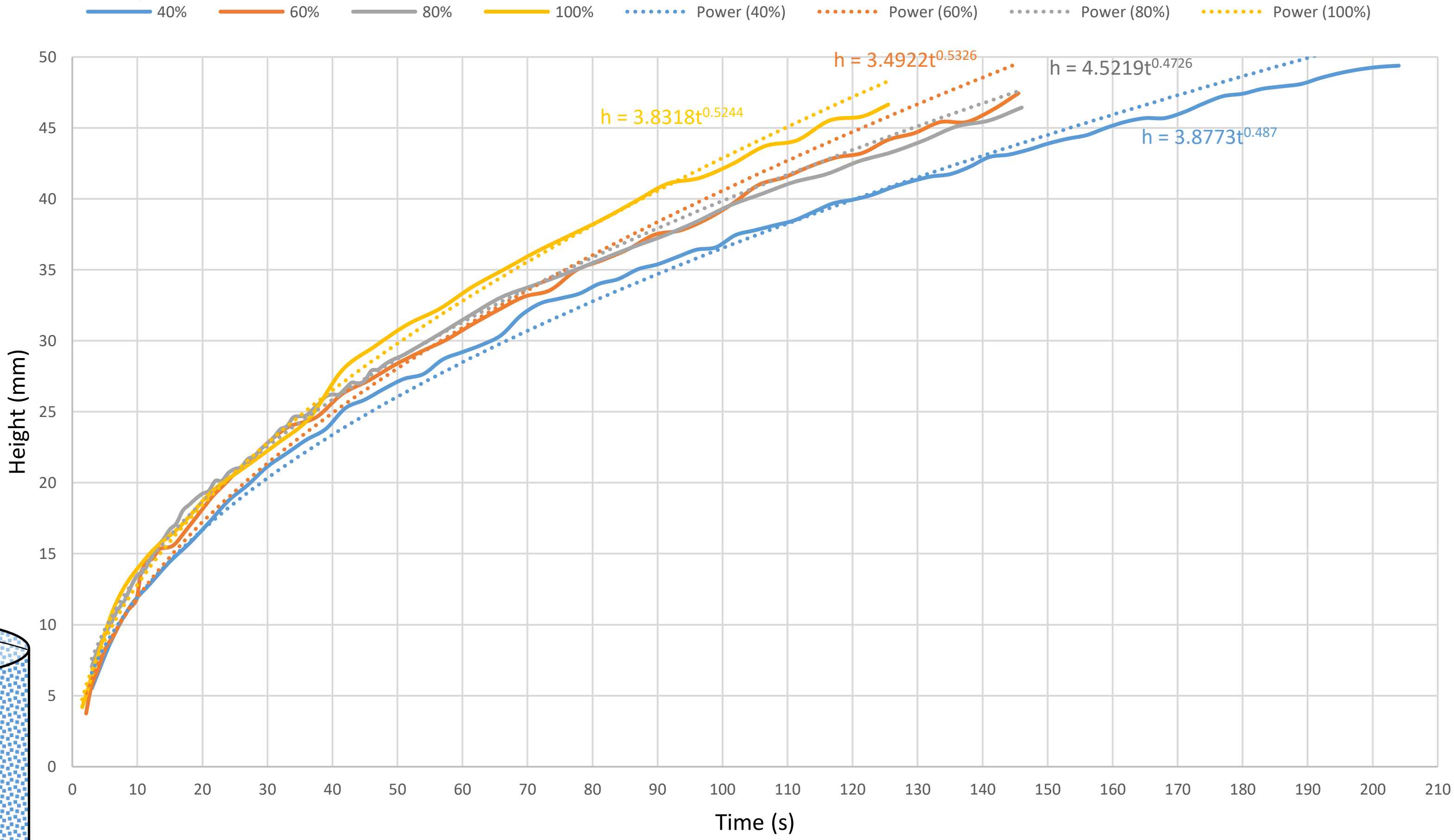
Results of Standard Liquid (Water) Inverted Trapezium



Dip region

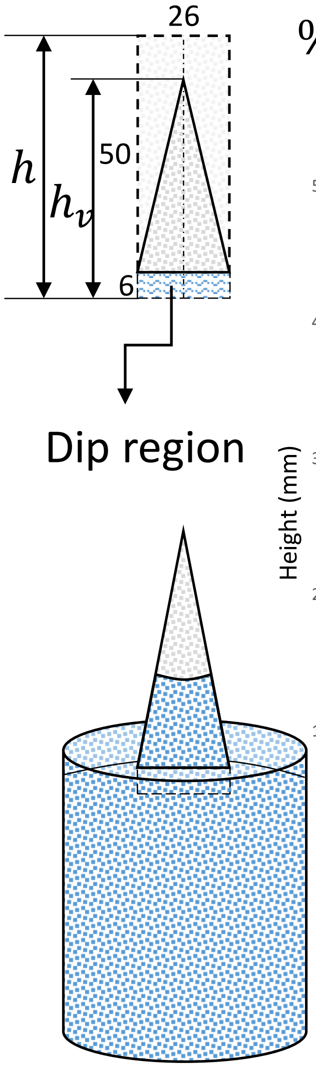


$$\% = \frac{l_h}{l_b} \times 100$$

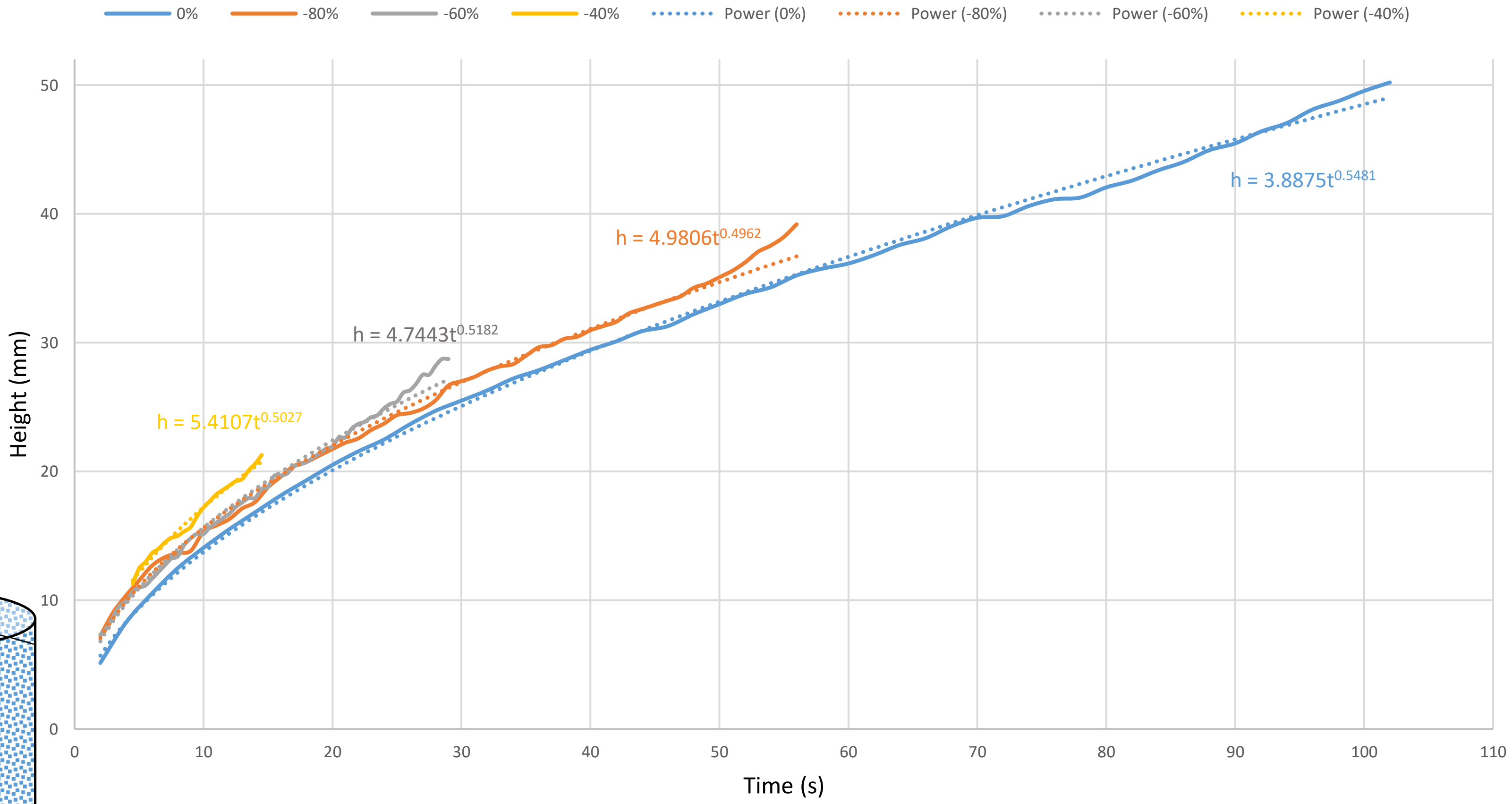


t ↓ with ↓ θ

Results of Standard Liquid (Water) – Triangle

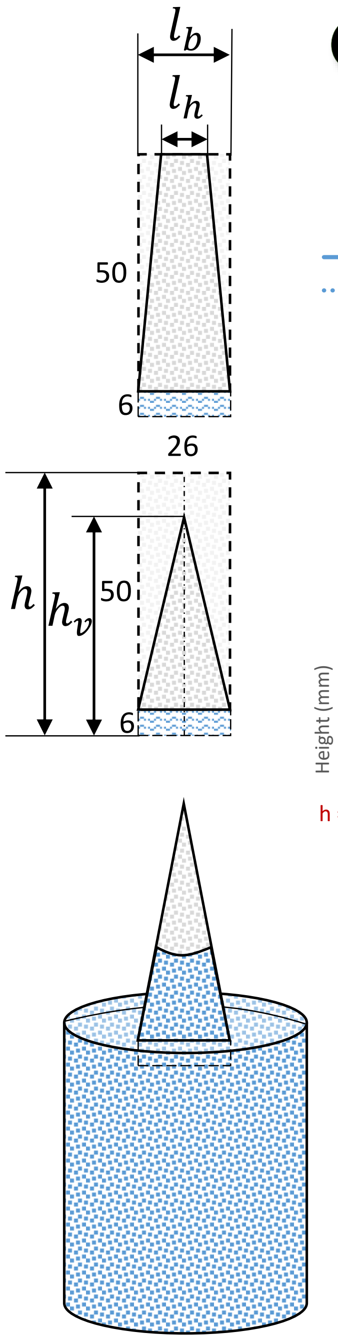


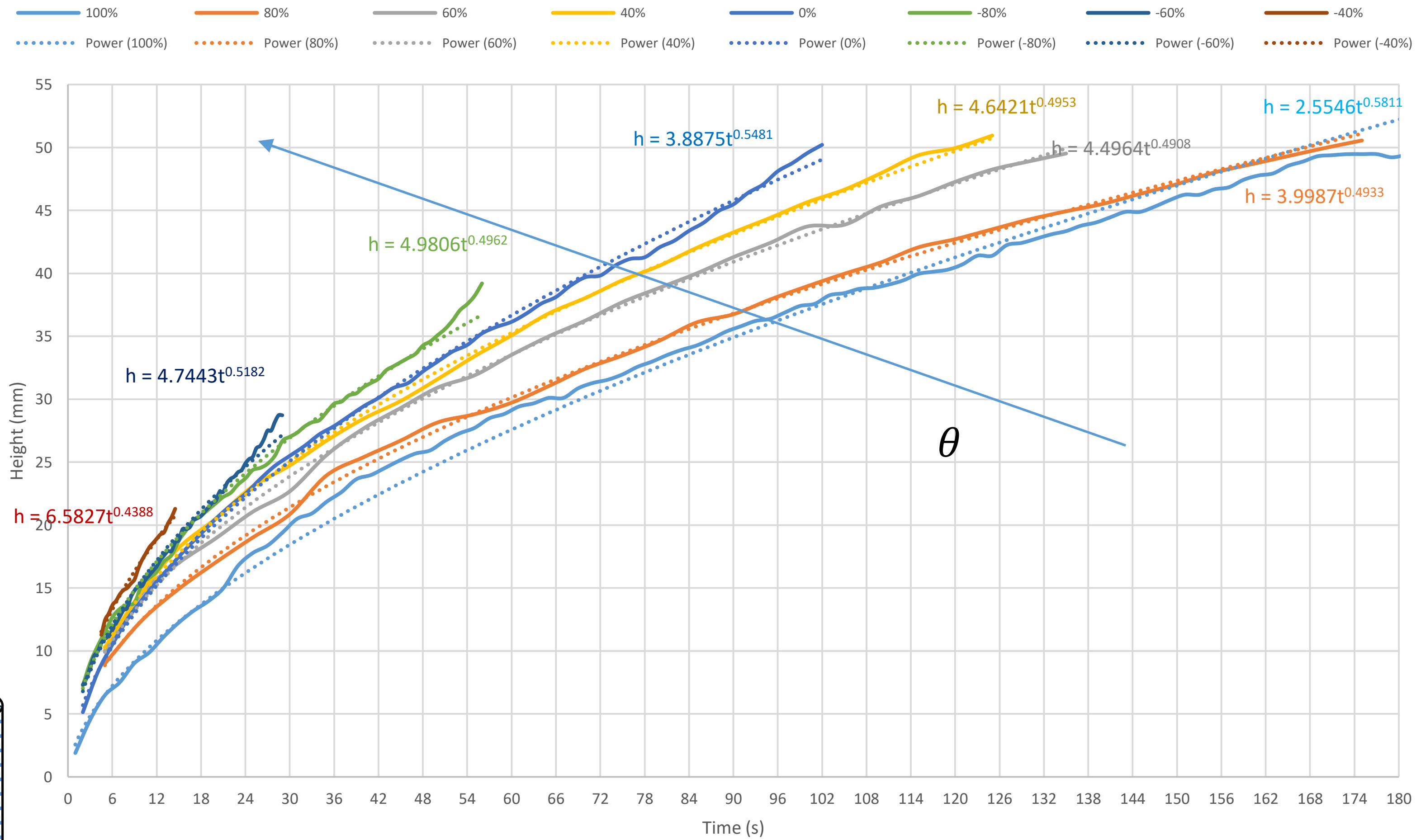
$$\% = -\frac{h_v}{h} \times 100$$



t ↓ with ↑ θ at tip of Δ ; $v \approx \propto$

Comparison of Standard Liquid (Water) Trapezium & Triangle





Short triangular geometries – BEST choice for liquid transportation

Comparison of Standard Liquid (Water) Trapezium & Triangle

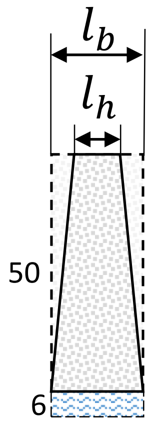
Shape	**%**	**Equation (h $= at^b$)**	
		a	b
Rectangle	100	5.22	0.4541
Trapezium	80	4.59	0.4700
	60	4.25	0.5013
	40	3.67	0.5375
Triangle	100	3.82	0.5494
	80	3.47	0.5852
	60	2.12	0.7339
	40	1.72	0.8131

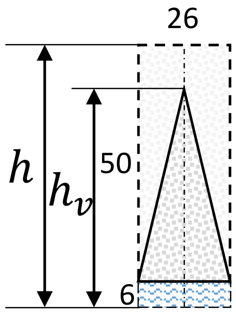
Triangular geometry does not follow $h \propto t^{0.5}$ law and in fact is closer to $h \propto t^{1}$

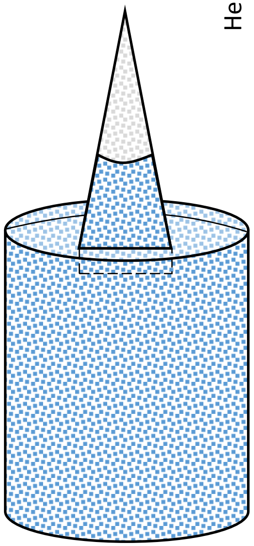
$h \propto t^{1}$ can be easily achieved with hyperbolically converging geometries

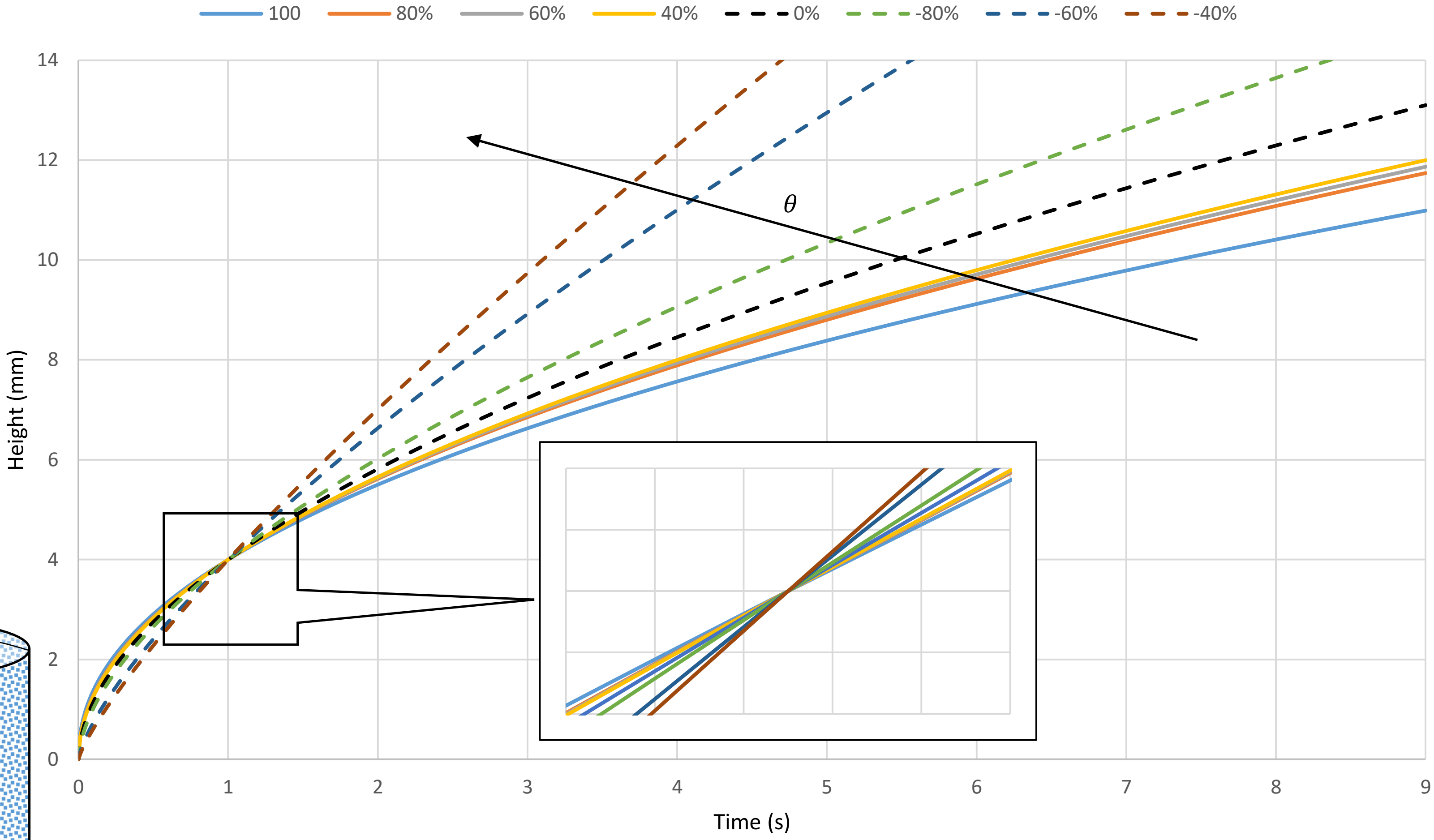
Careful choice of geometry – think beyond $h \propto t^{0.5}$ law !

Comparison of Standard Liquid (Water) Trapezium & Triangle (Ideal)









Increasing rate of liquid rise – Triangular > Trapezium > Rectangular

Conclusions

1. Liquid (Water, Pentane, and Acetone) rise classical experiments – a revisit.
2. Simple 2-D porous networks to model Heat pipes, and its variants.
3. Various geometries – Rectangular, Trapezium, Triangles.
4. Initially, the liquid rise is same regardless of size and shape of filter paper.
5. Across all the experiments, $h \propto t^b, 0.3 < b < 1$
6. For the same time, converging filter-papers showed higher h.
7. Converging geometries – improve the '*critical heat load*' of wicks.
8. Rapid liquid transportation – Triangular geometries are preferred.
9. For same time, diverging filter-papers showed lower h.
10. IR radiative heating to boosts rate of evaporation.
11. Heating load changes the steady state interface position.
12. Evaporation is indeed a limiting factor in wicks.
13. Huge implications in electronic cooling industries (Space crafts).

Future Works

1. Different porosity and permeability systems.
2. Horizontal capillary spreading (non-linearly increasing area).
3. Heating method – conductive (closer to real heat pipes).
4. Mathematical model.

Important Contributions

1. Laplace (1806)
2. Lucas (1918)
3. Edward W Washburn (1921)
4. Levine (1980)
5. B. V. Zhmud (2000)
6. A Ponomarenko (2011)

Acknowledgements

1. Indian Institute of Science (IISc)

2. Prof. J. H. Arakeri (IISc)

3. University Visvesvaraya College of Engineering (UVCE)