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# Pot-in-Pot refridgerator

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# Task

The 'pot-in-pot refrigerator' is a device that keeps food cool using the principle of evaporative cooling.

It consists of a pot placed inside a bigger pot with the space between them filled with a wet porous material, e.g. sand.

How might one achieve the best cooling effect?

→ *Low temperature*
→ *Fast cooling*

# Mechanism

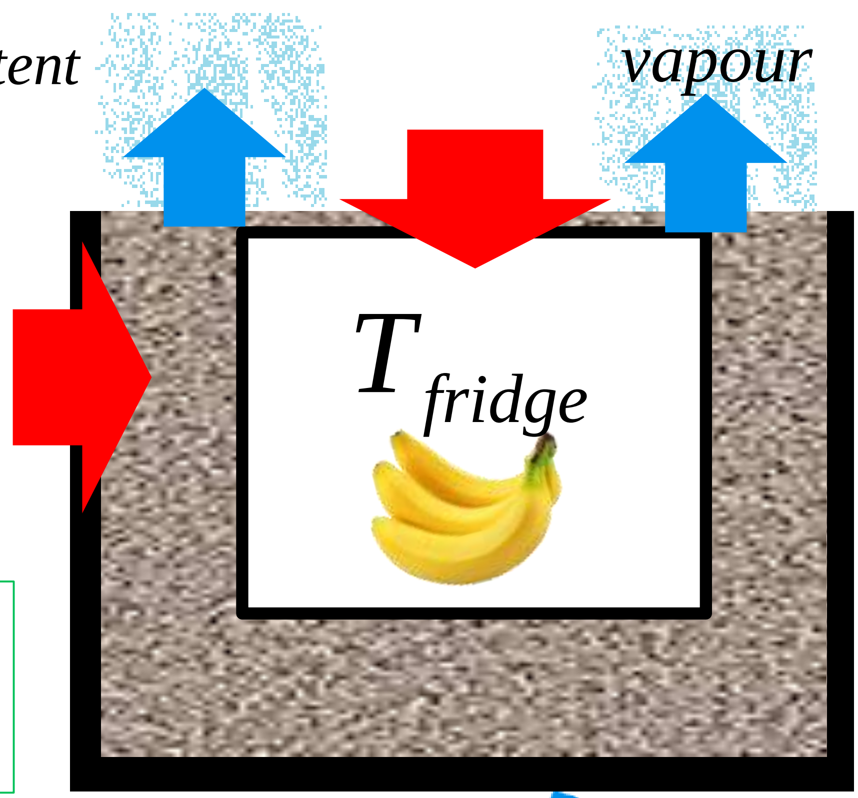
Wet porous material:

Evaporation → latent heat → cooling

$Q_{latent}$

Heat transfer from the environment

$Q_{transfered}$

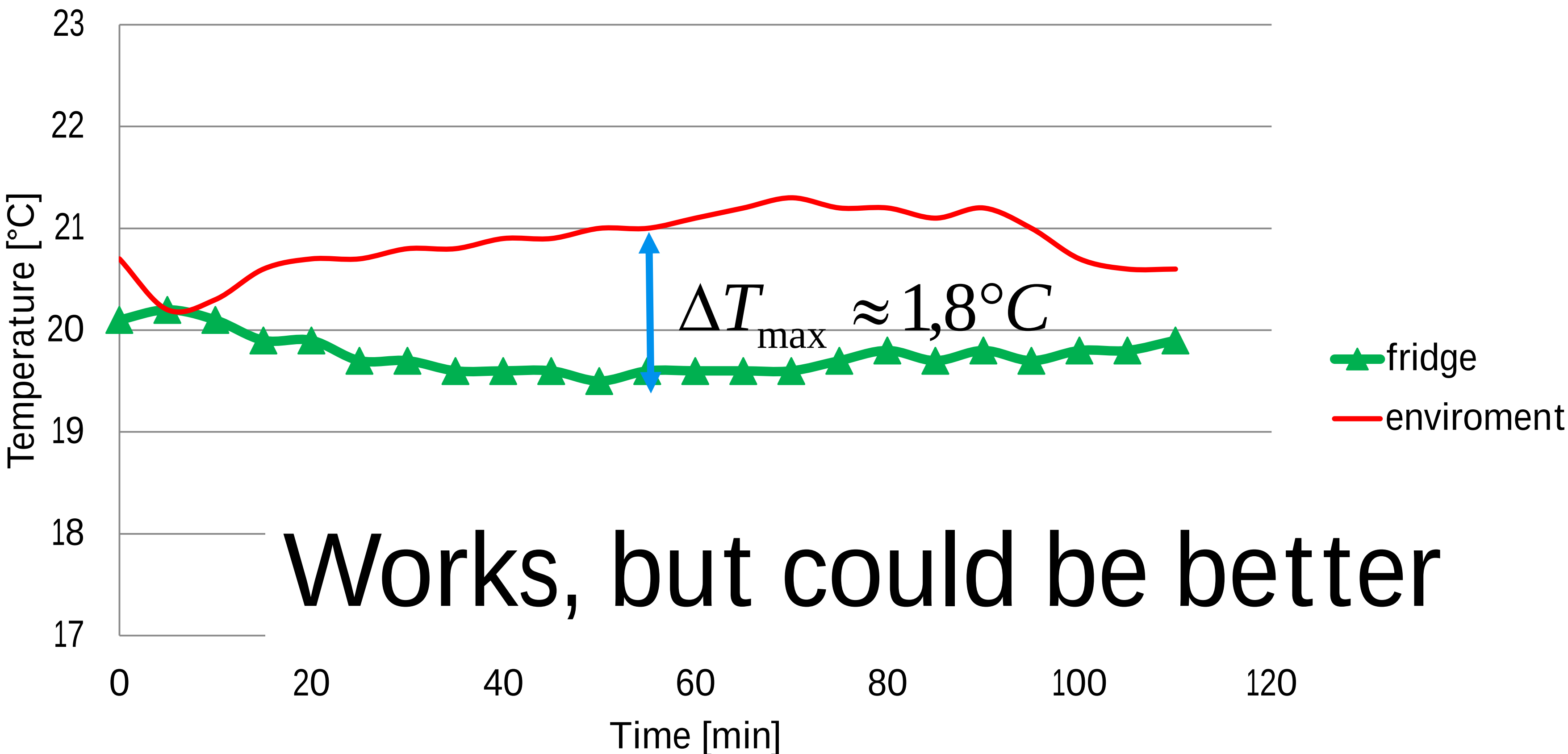



Equillibrium:

$$T_{fridge} < T_{environment}$$

# Preliminary Experiment

- Porous material: sand

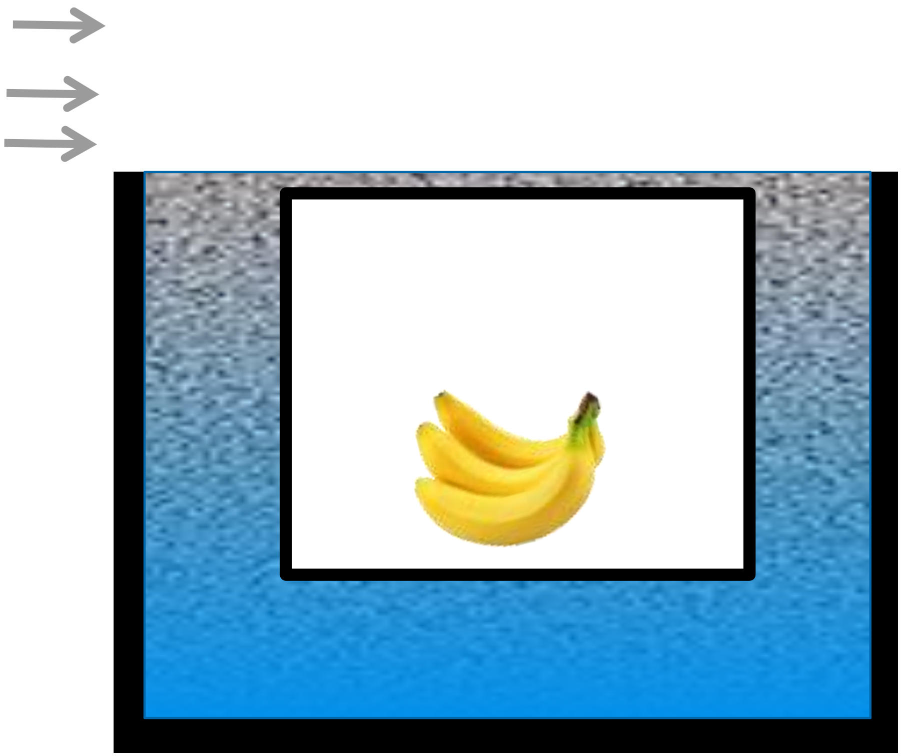



Works, but could be better

# Evaporation requirements

Must be wet
(capillarity)

Exposed to air flow

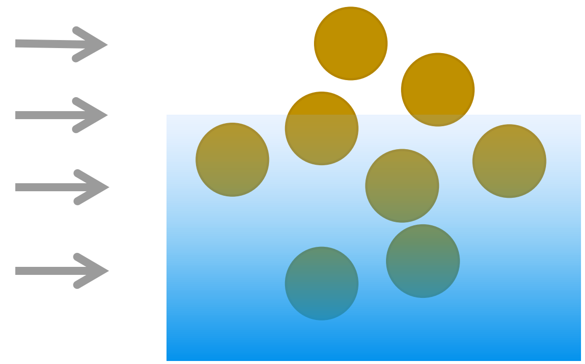


# Sand: a granular material

Big granules:

→ Better airflow ✓

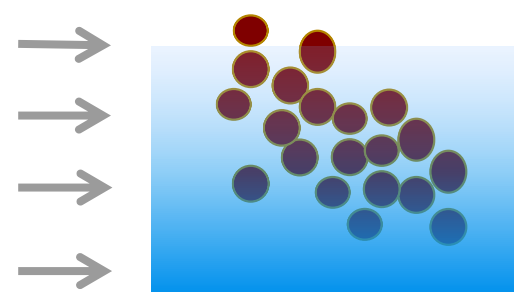
→ Water drains down ✗



Small granules:

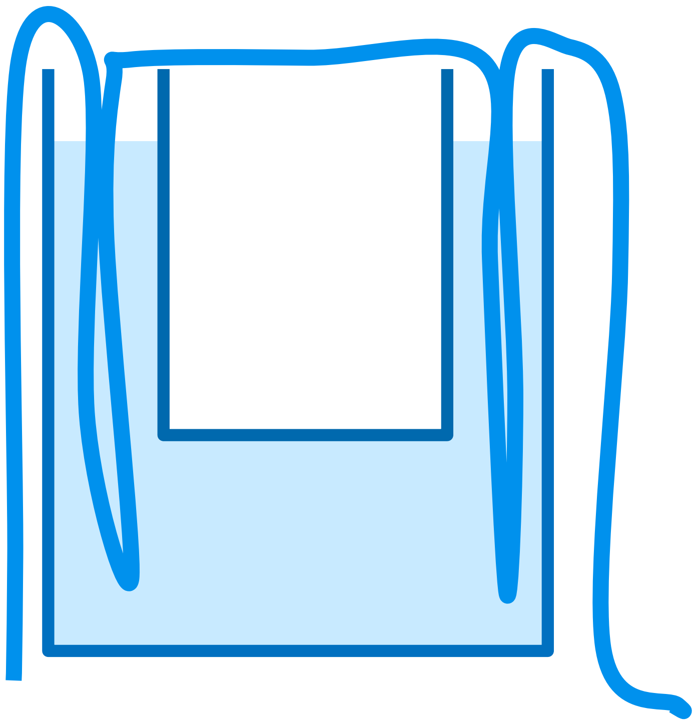
→ Can soak with water ✓

→ Little space for airflow ✗

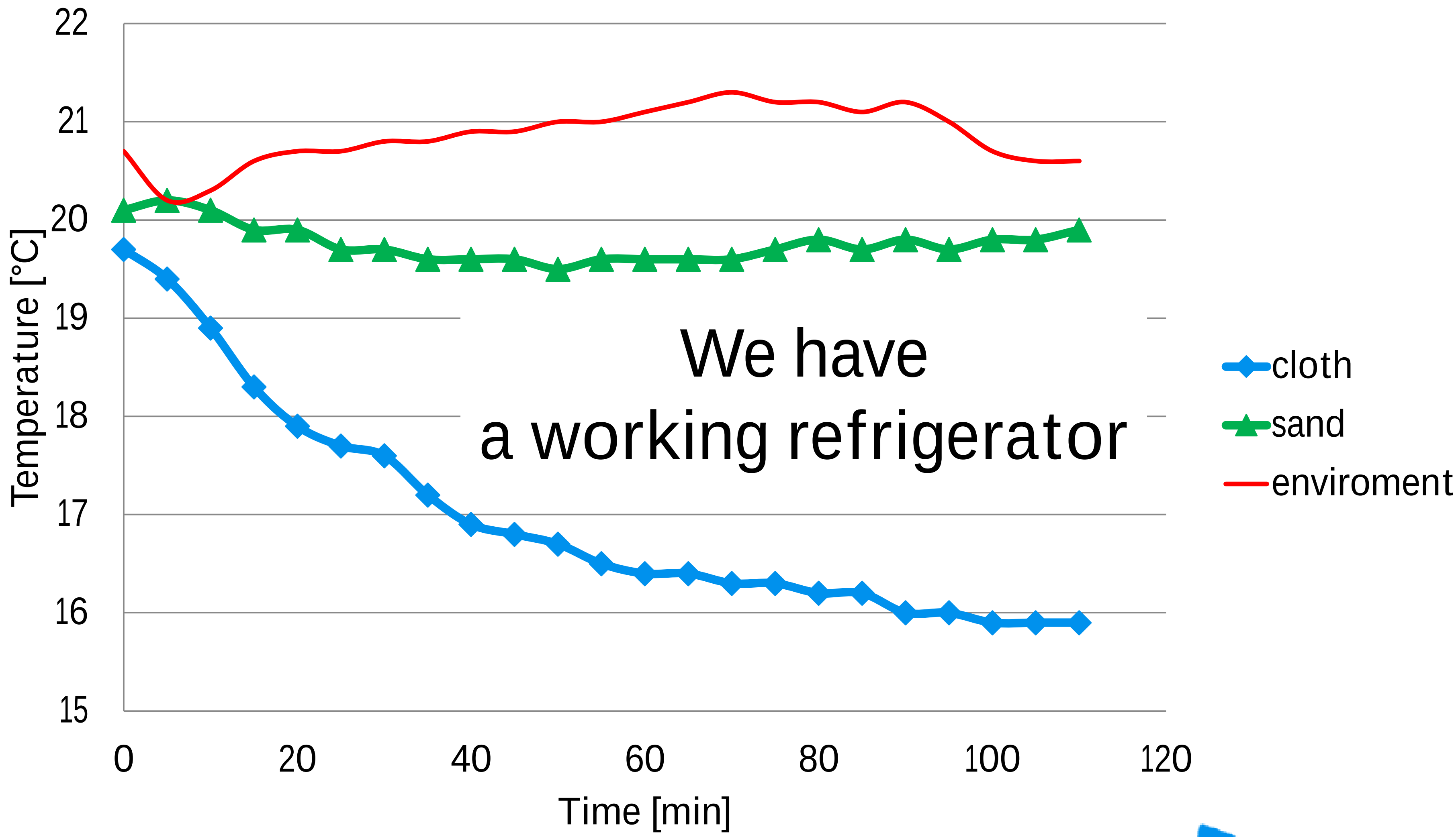


# Other kind of porous material: Cloth

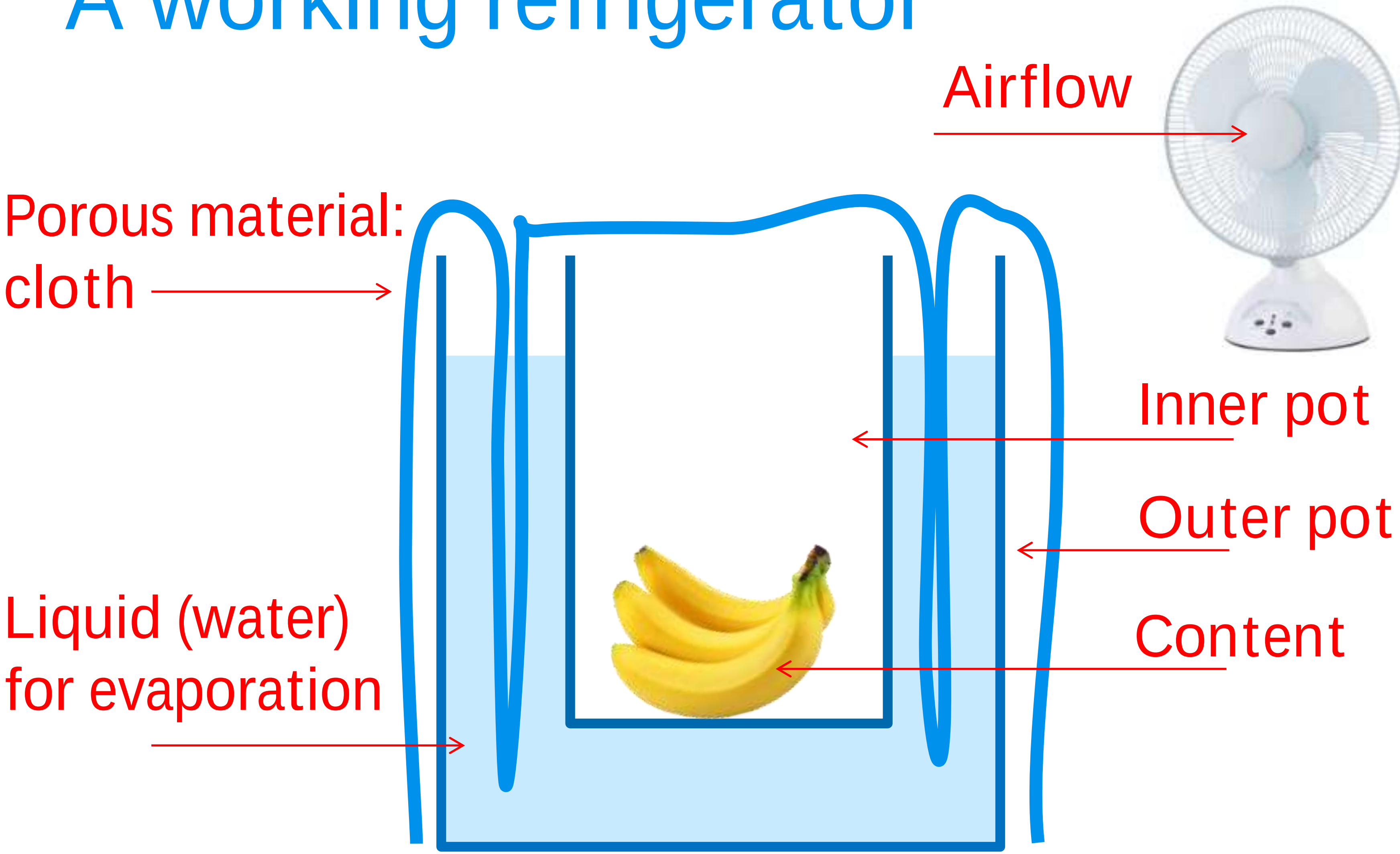
- Gets soaked with water
- Can be exposed to air flow on sufficient area



# Cloth vs. sand: the difference



# A working refrigerator



# Task

*"How might one achieve the best cooling effect?"*

*→ Low temperature*
*→ Fast cooling*

- Simple model of the cooling
- Experimentally verify & optimize
- Estimate the best possible cooling

# MODEL OF THE COOLING

# Model of the cooling effect

- Evaporation rate: $dm = ASvdt$
  $A$: related to volatility of the liquid (in air)

- Heat transferred
  from the surroundings: $\mathrm{dQ} = BSv\Delta T dt$
  $B$: related to thermal conductivity, capacity of air

| | |
|---|---|
| $S$ | Surface area |
| $v$ | Air flow speed |
| $\Delta T$ | Temperature difference |

# Model of the cooling

Calorimetry:

$$AS v \lambda dt - BS v \Delta T dt = -C dT$$

$$T = T_{air} - \frac{A\lambda}{B}\left(1 - e^{-\frac{BSv}{C}t}\right)$$

Final temperature drop: $\Delta T = \frac{A\lambda}{B}$

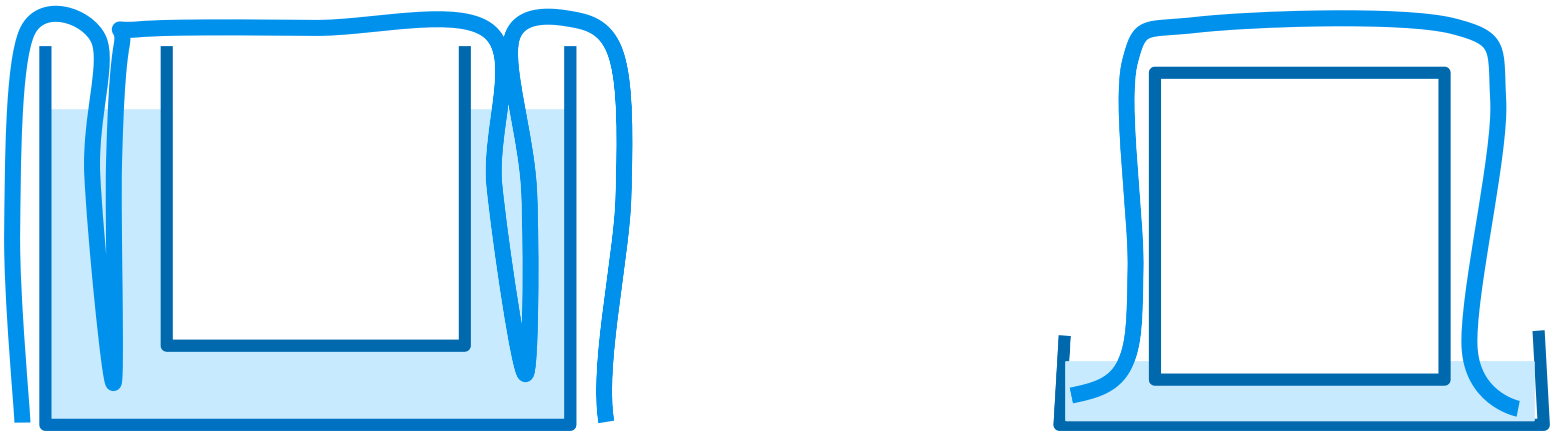
Speed of cooling: $\frac{BSv}{C}$

$\lambda$ = latent heat

C = thermal capacity of fridge

# EXPERIMENTAL VERIFICATION & INVESTIGATION

# 1. High vs. low outer pot



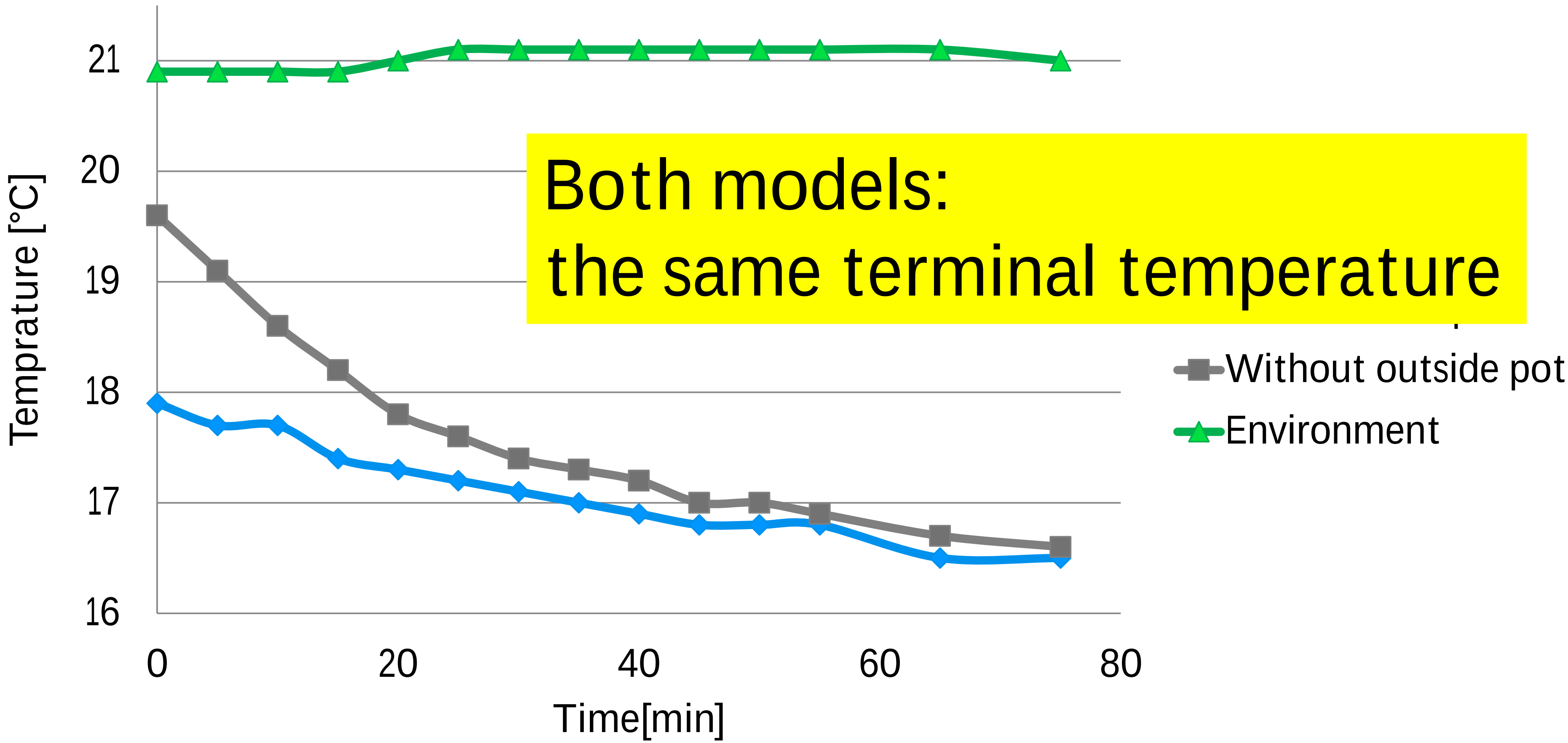
- Terminal temperature: $\Delta T = \dfrac{A\lambda}{B}$

  depends on materials only → Equal

- Cooling rate: $\dfrac{BSv}{C}$

  more water → bigger $C$ → slower cooling

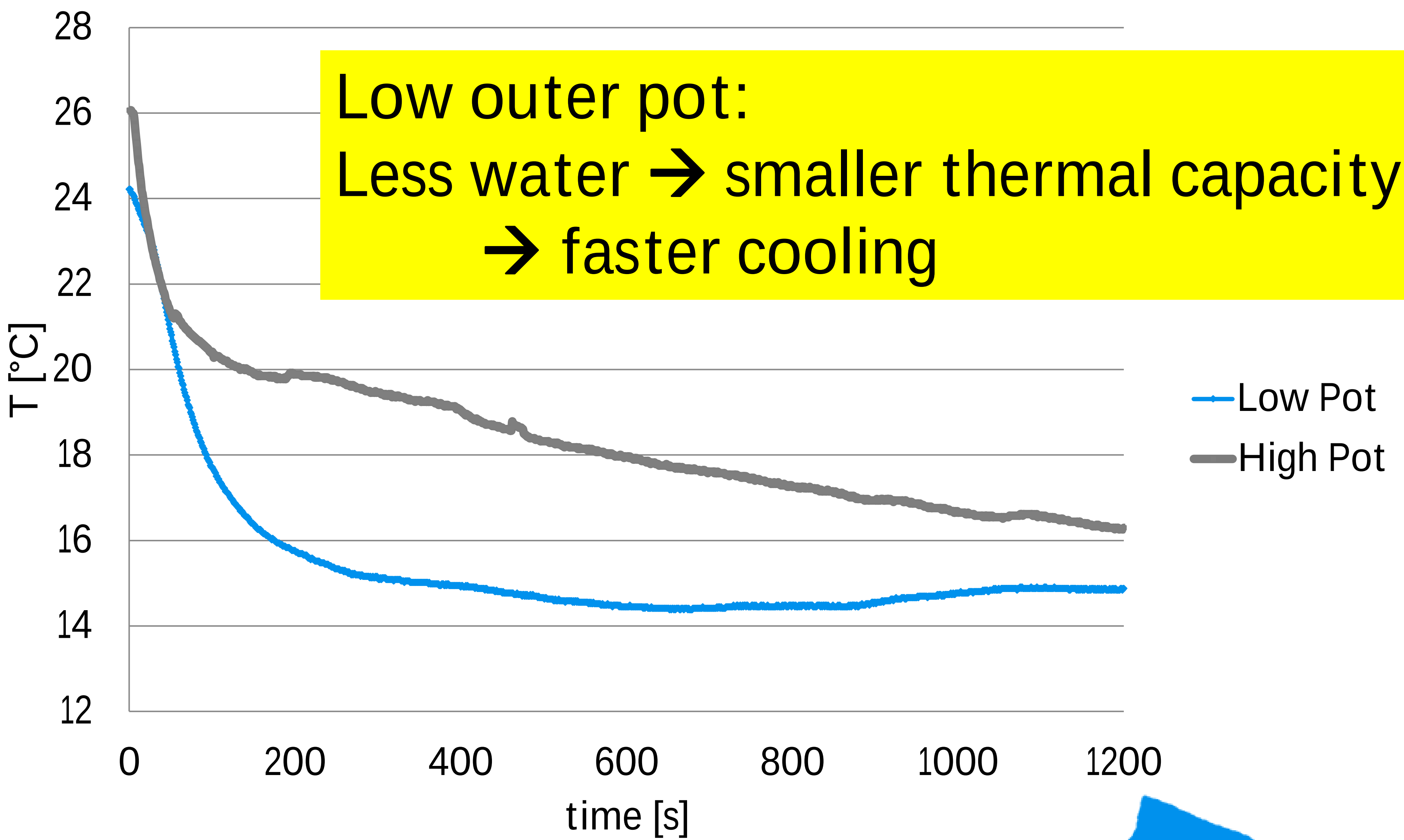
# High vs. low pot: final temperature




Both models:
the same terminal temperature

# High vs. low pot: rate of cooling

Low outer pot:
Less water → smaller thermal capacity
→ faster cooling



# 2. Size and shape of the fridge

Terminal temperature:

$$\Delta T = \frac{A\lambda}{B}$$ Independent of size/shape

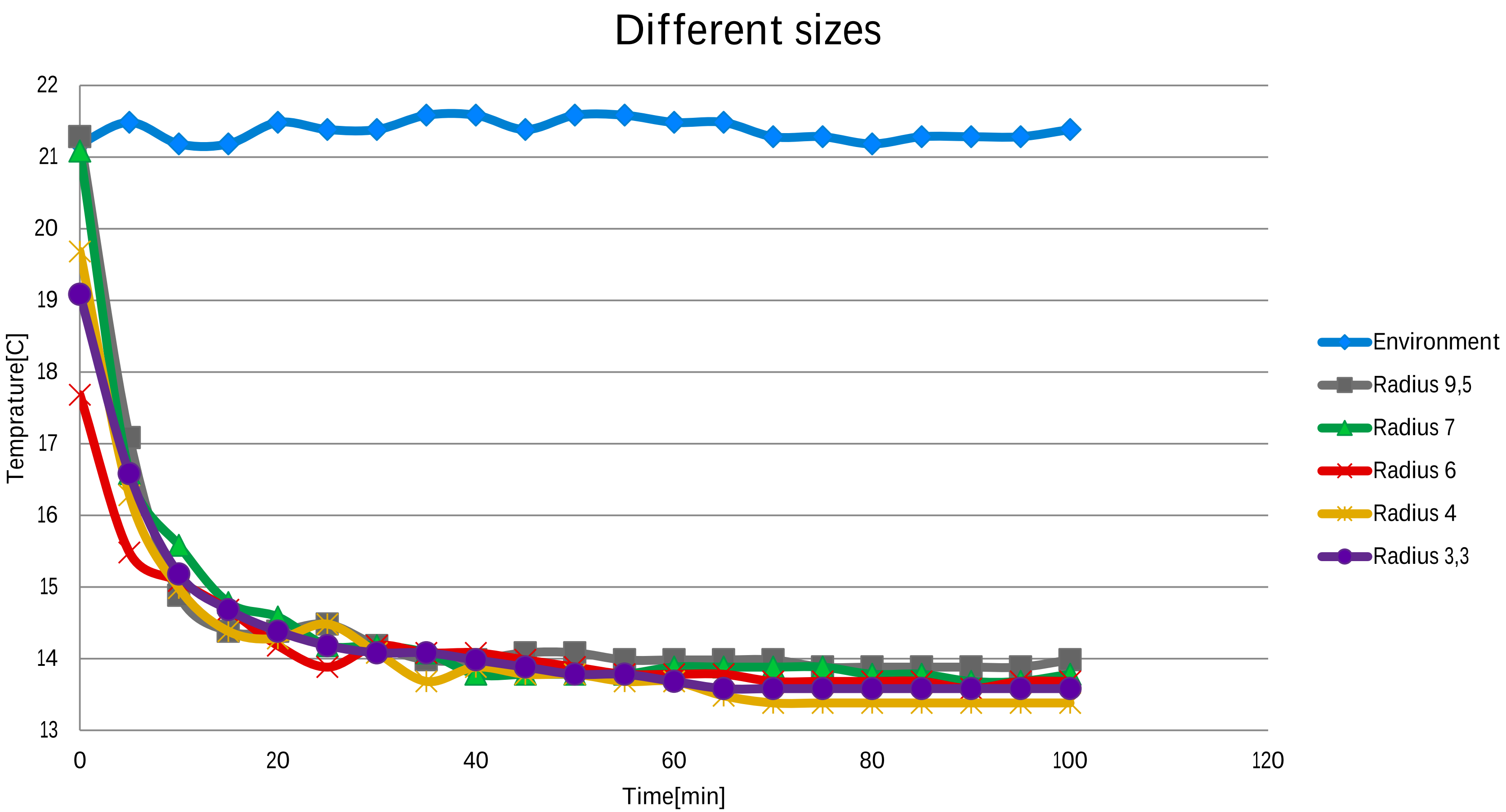
Speed of cooling:

$$\frac{BSv}{C}$$ Independent of size/shape

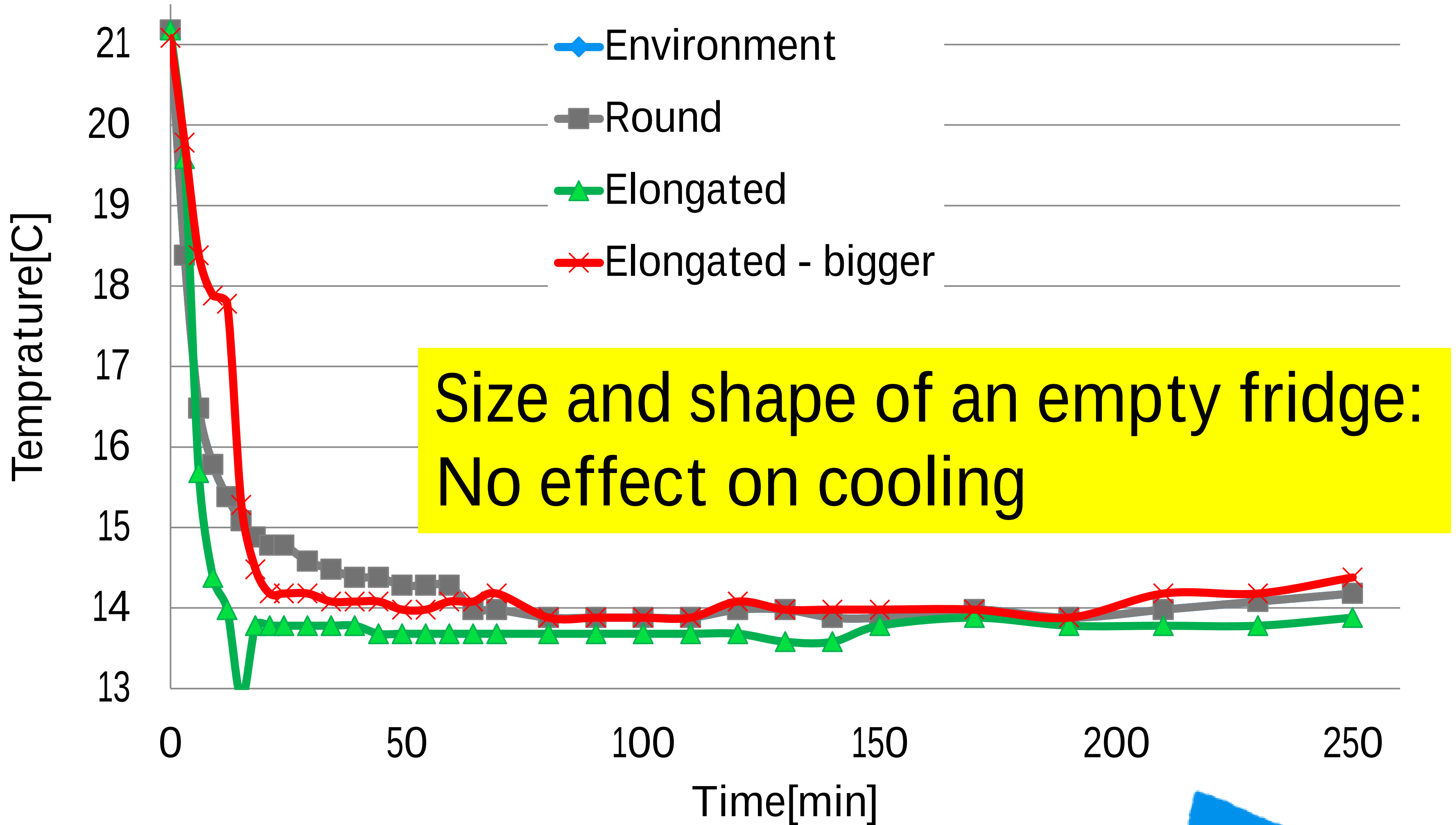
Empty refrigerator:
Proportional to surface area

# Effect of different sizes

# Effect of different size



# Effect of different shapes



# 3. What's inside

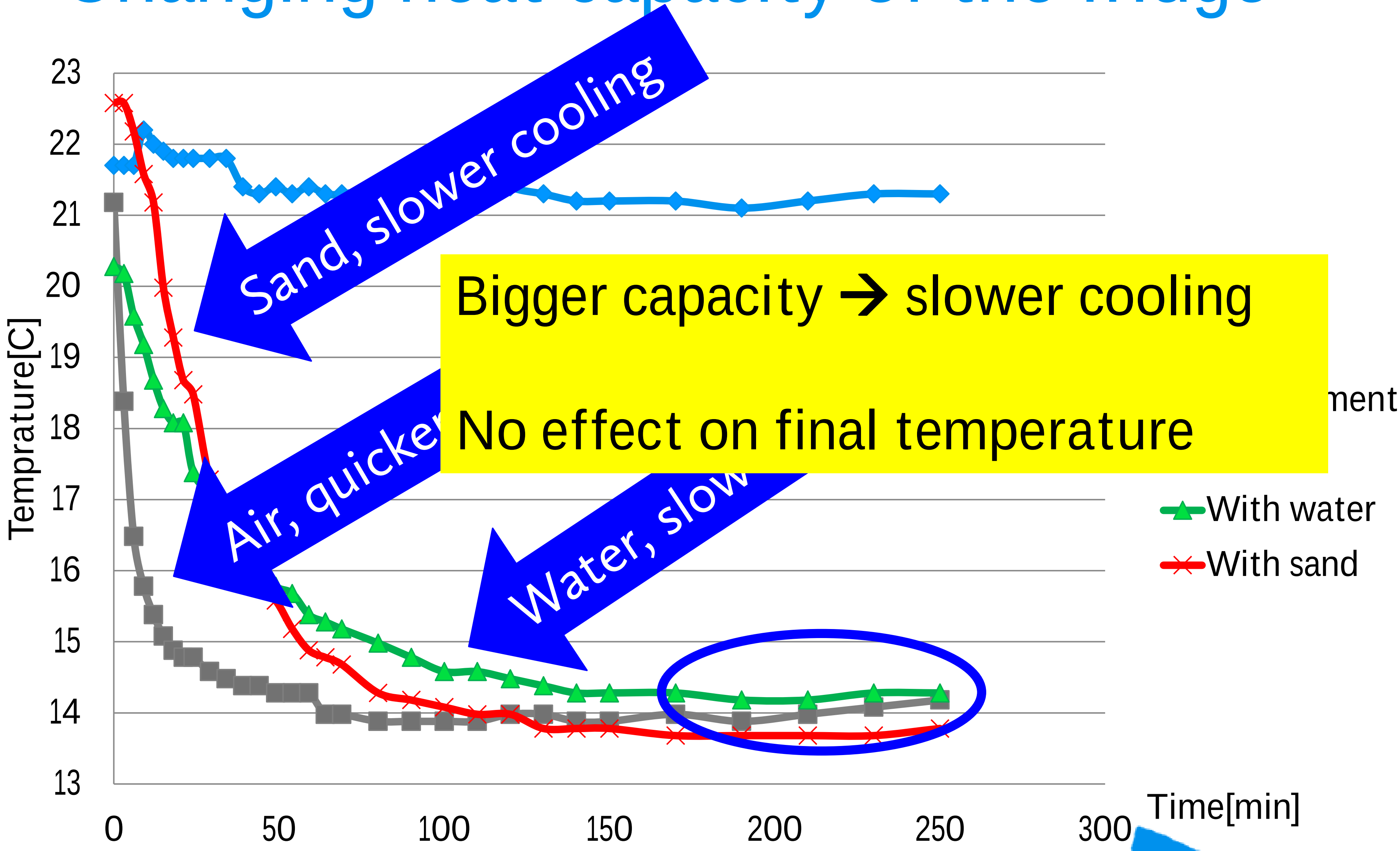
Terminal temperature:

$$\Delta T = \frac{A\lambda}{B}$$ Independent of content

Speed of cooling:

$$\frac{BSv}{C}$$ High capacity → slower cooling

# Changing heat capacity of the fridge



# 4. Different liquid

Terminal temperature:

$$\Delta T = \frac{A\lambda}{B}$$

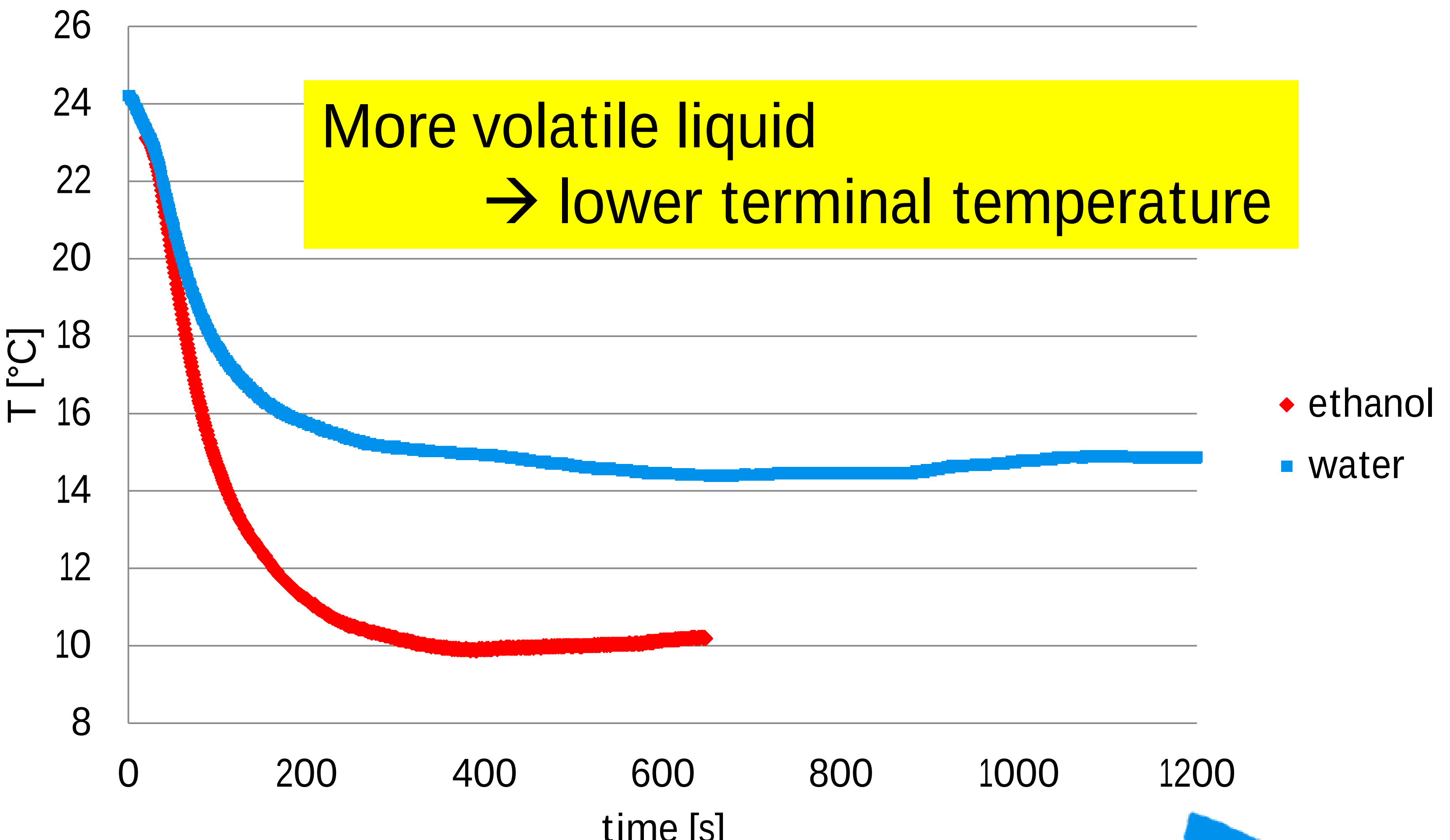
Grows with volatility & latent heat

Speed of cooling:

$$\frac{BSv}{C}$$

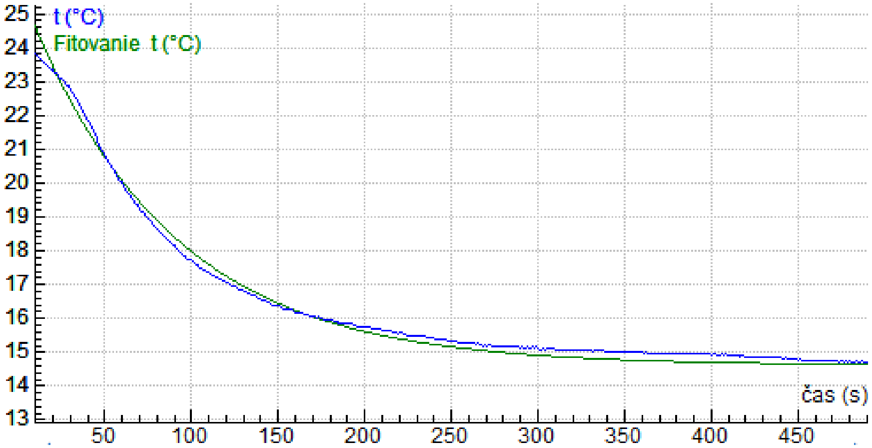
Independent of liquid
(only a small capacity difference)

# Water VS. Etanol:



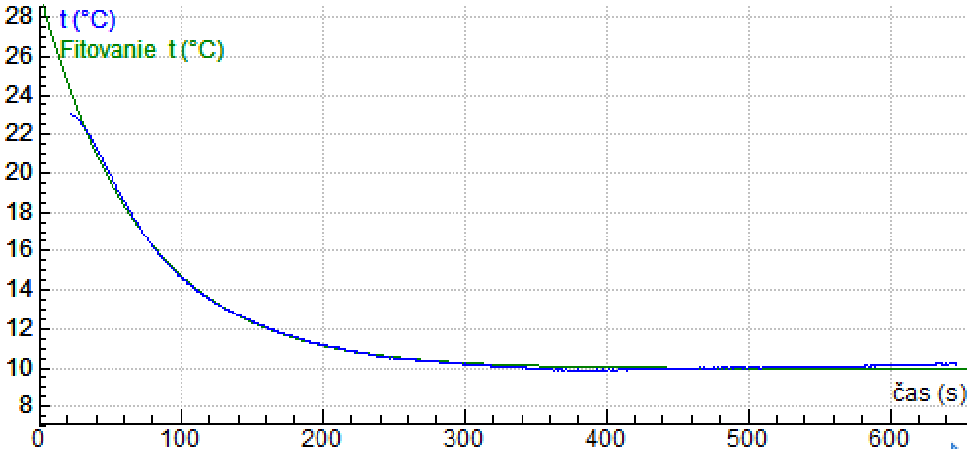
# Water vs. ethanol: exponential fit

## Water




$$T \approx 10.6 * \exp(-0.012t) + 14.8$$

## Ethanol




$$T \approx 19.4 * \exp(-0.014t) + 10.0$$

**Different liquids → similar speed of cooling**

Slight difference: different thermal capacity

# WHAT IS THE BEST POSSIBLE EFFECT?

# Minimal temperature estimation

Analogical phenomenon:

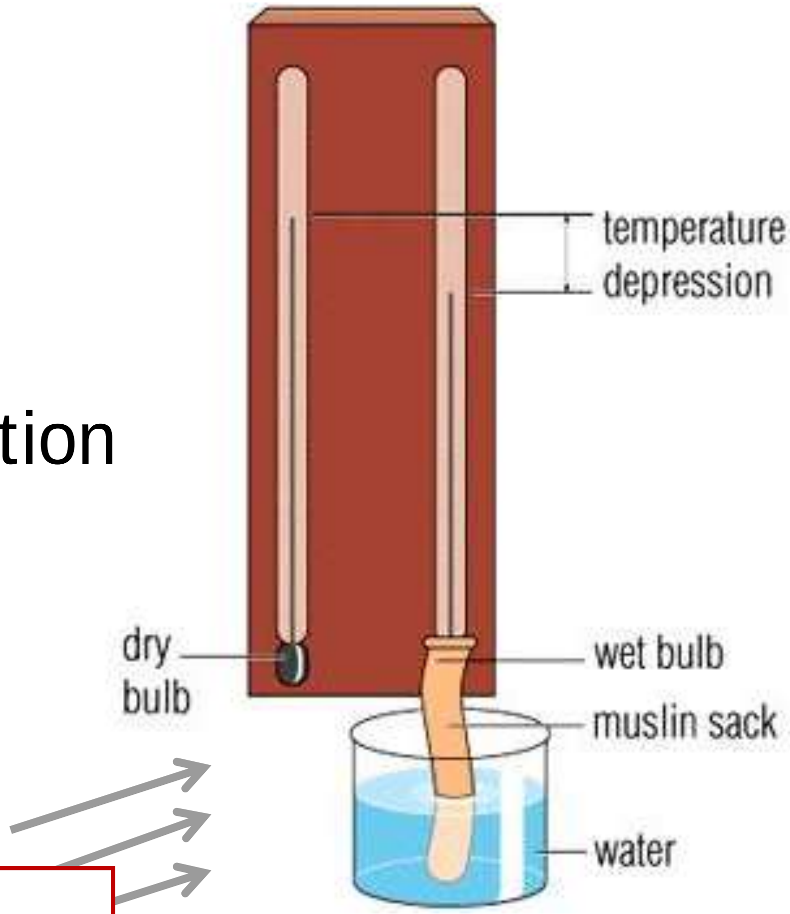
## Assman psychrometer

- Wet and dry thermometer
- Wet is cooler due to evaporation
- Equilibrium state:

$$dQ_{transfered} = dQ_{latent}$$

- Solution:

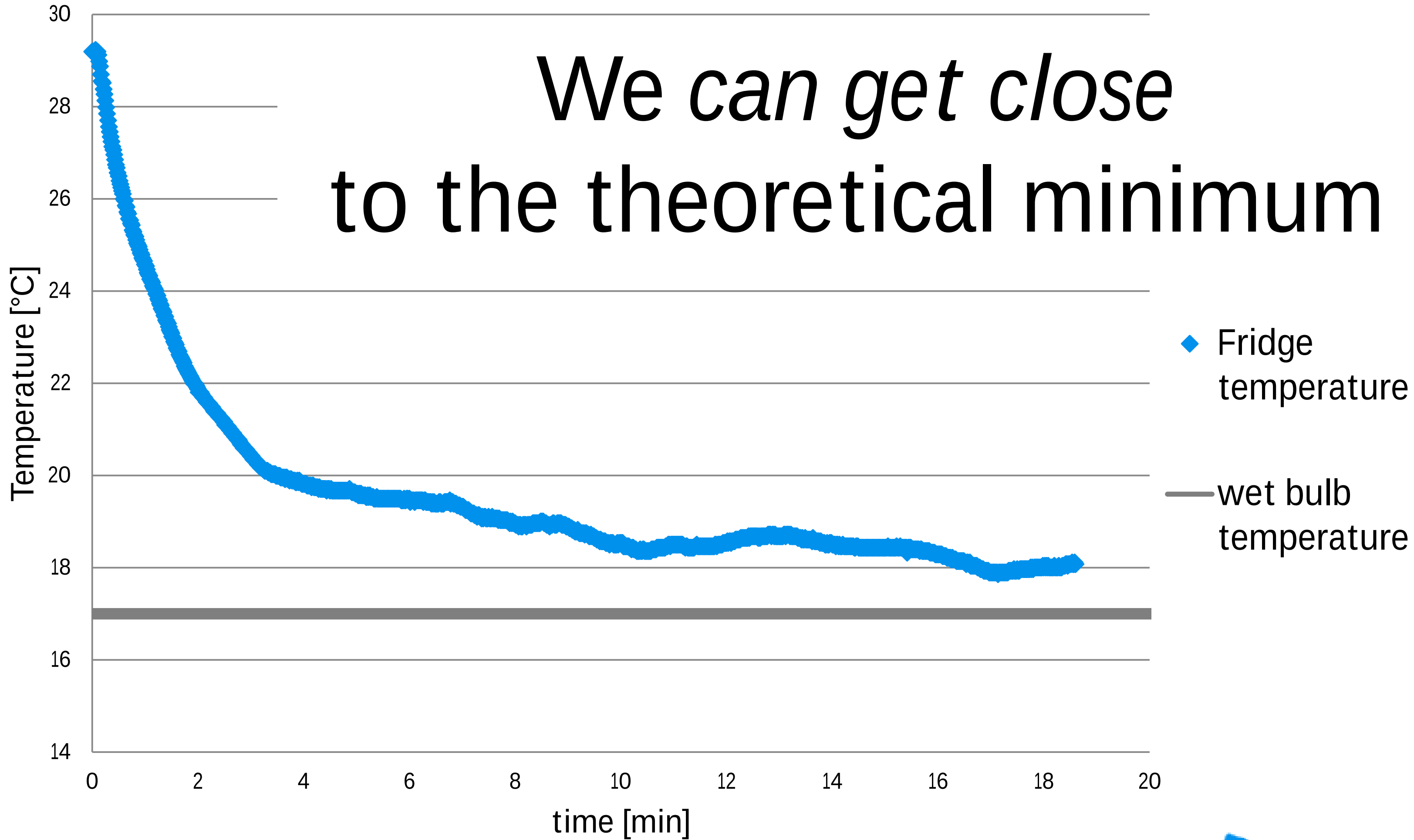
$$\frac{M_{air}}{p_{atm}}[E(T_{fridgel}) - e_{air}] = c_p(T_{air} - T_{fridge})$$



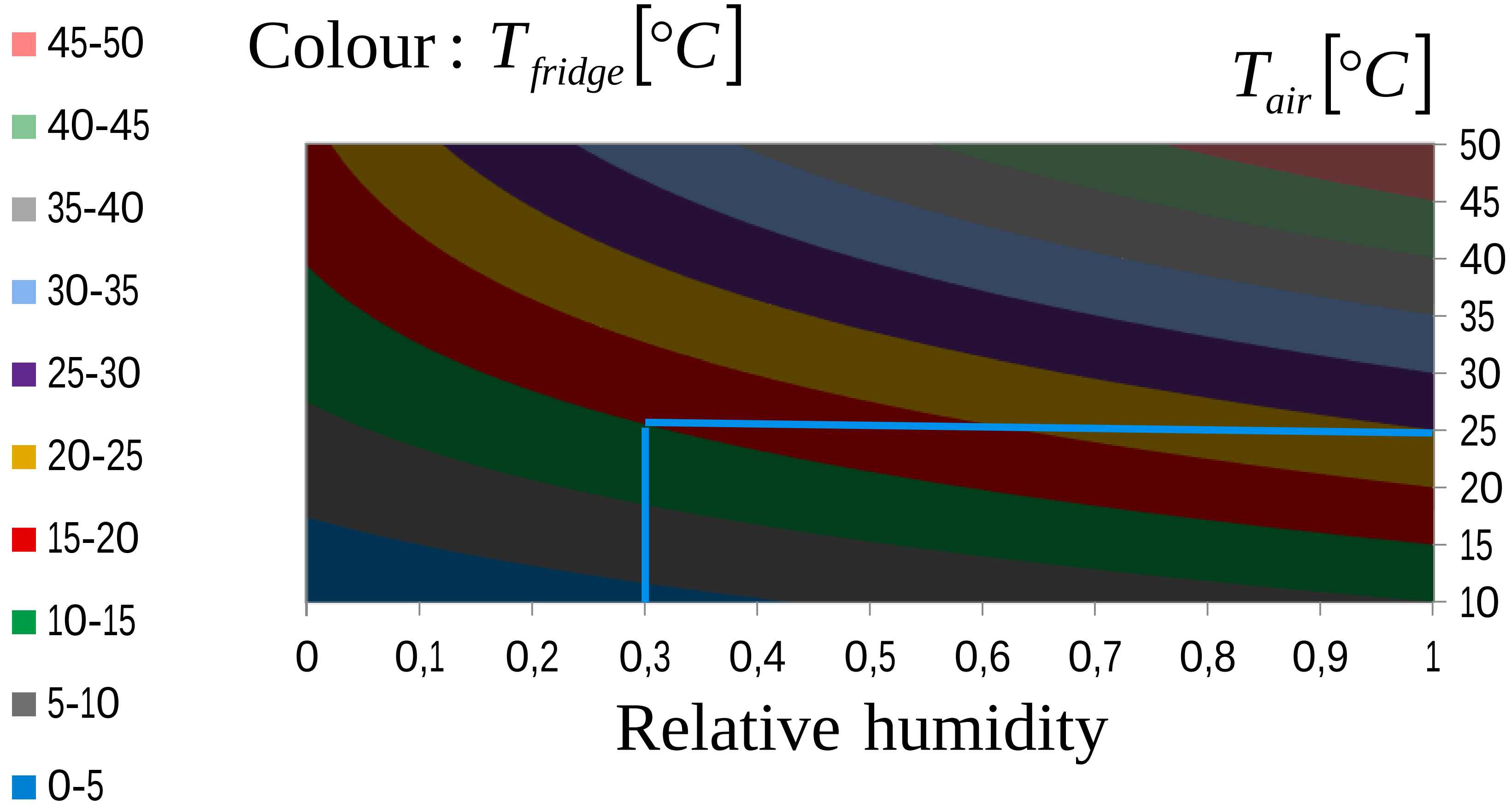

Sufficient airflow

# Wet bulb vs. refrigerator

We *can get close*
to the theoretical minimum



# Minimal achievable temperature



# Best cooling effect

$$T = T_{air} - \frac{A\lambda}{B}\left(1 - e^{-\frac{BSv}{C}t}\right)$$

Minimal temperature

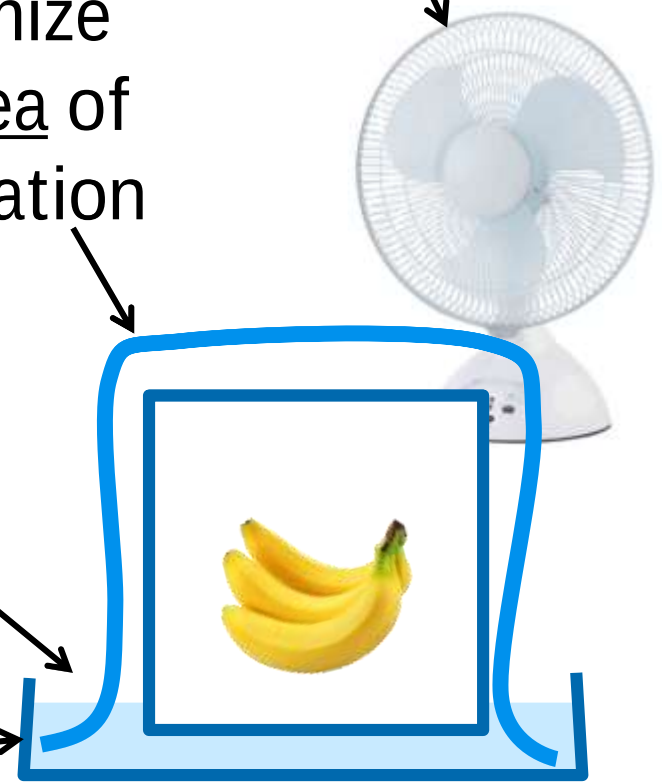
speed

Sufficient air flow

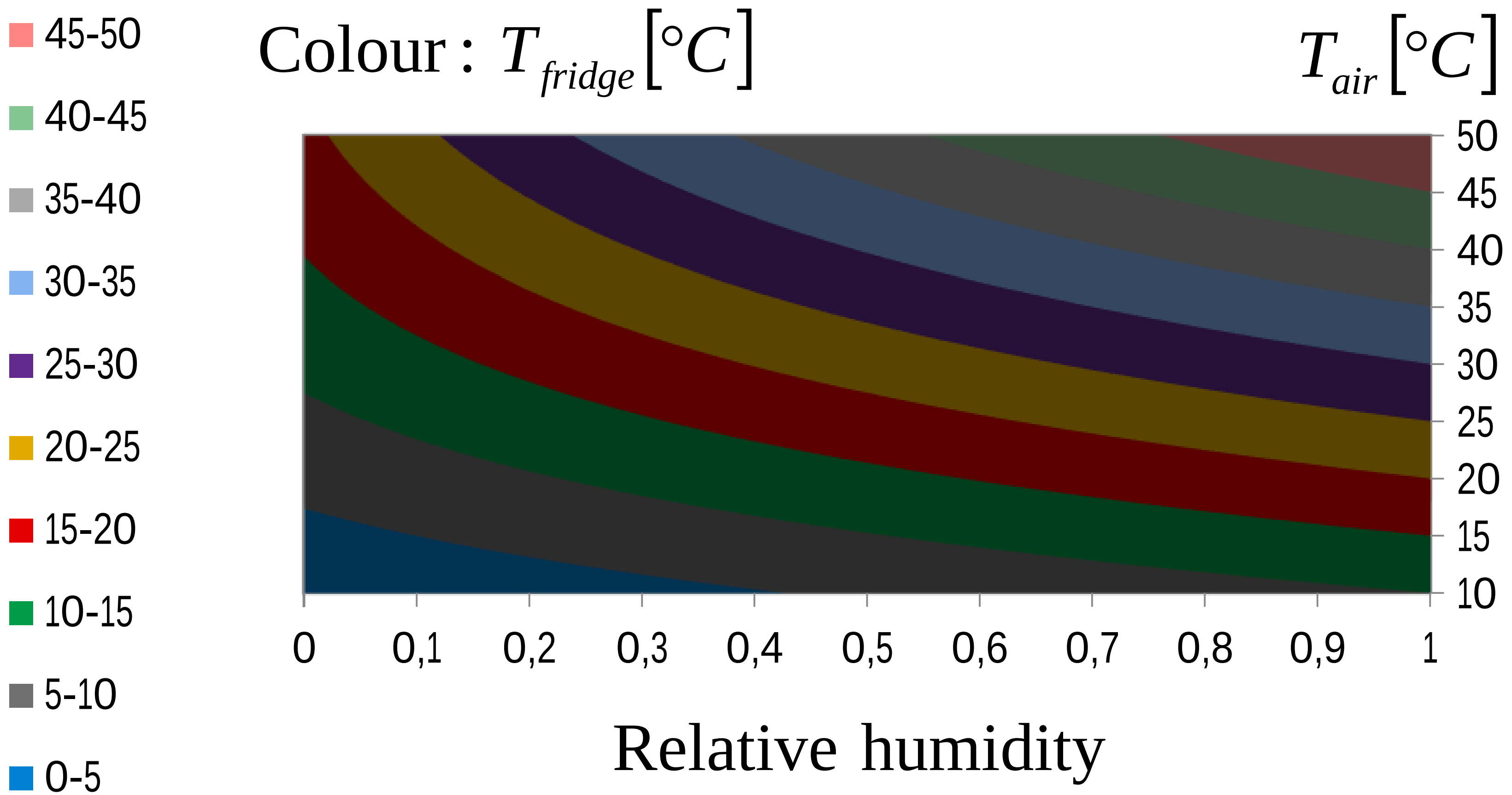
Maximize the area of evaporation

volatile liquid with low concentration in air (eg. Ethanol)

Minimise thermal capacity of the fridge (eg. Low outer pot)



# Thank you for your attention



# APPENDICES

# Assman psychrometer theory

Assumptions:

- Air cools to $T_{fridge}$; vapor pressure saturates (thanks to fast airflow)
- Equilibrium of heat flow: $dQ_{transfered} = dQ_{latent}$

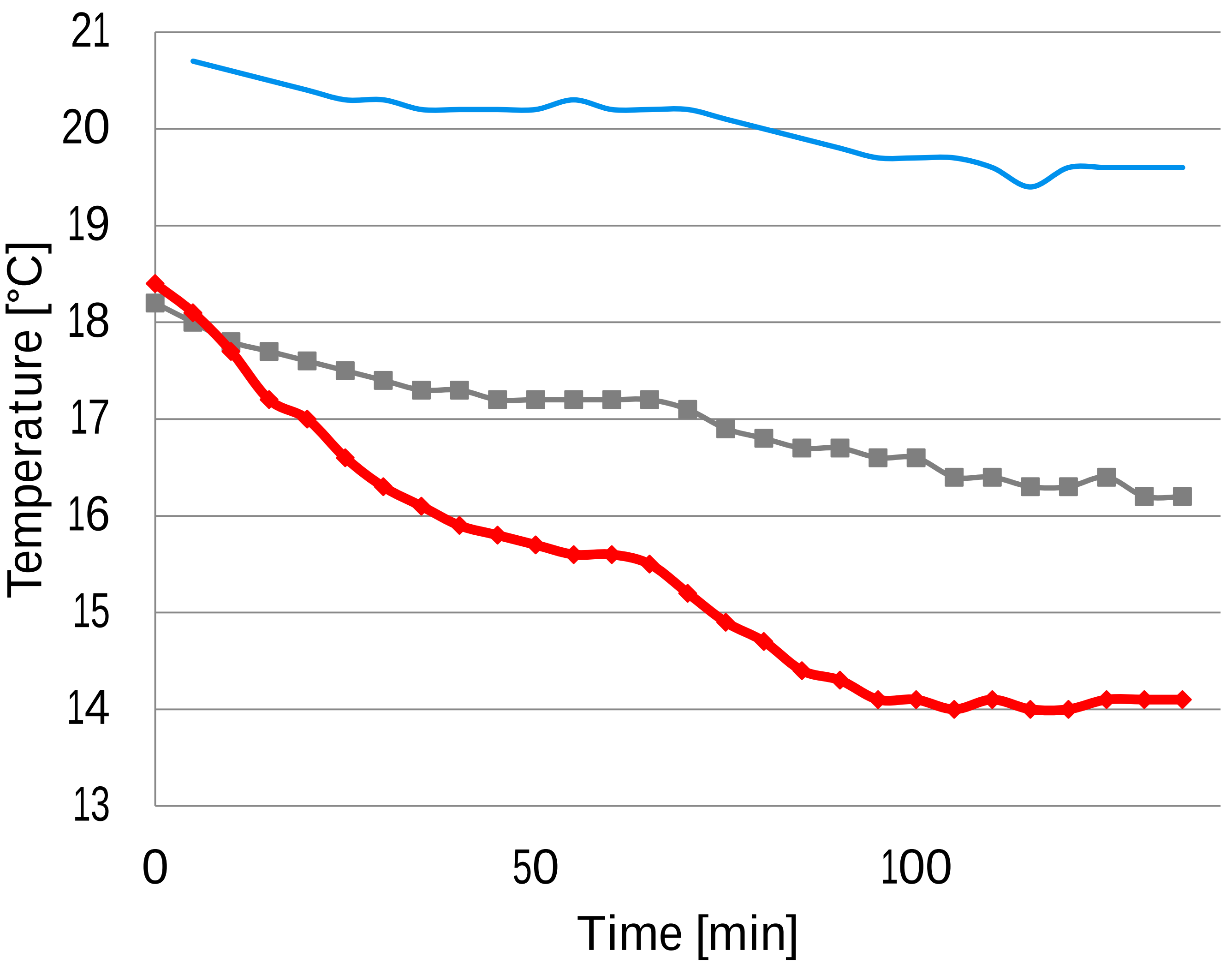
$$\frac{M_{air}}{p_{atm}}[E(T_{fridgel}) - e_{air}] = c_p(T_{air} - T_{fridge})$$

- Numerically solve for $T_{fridge}$ (complicated function $E(T)$)


Wet bulb

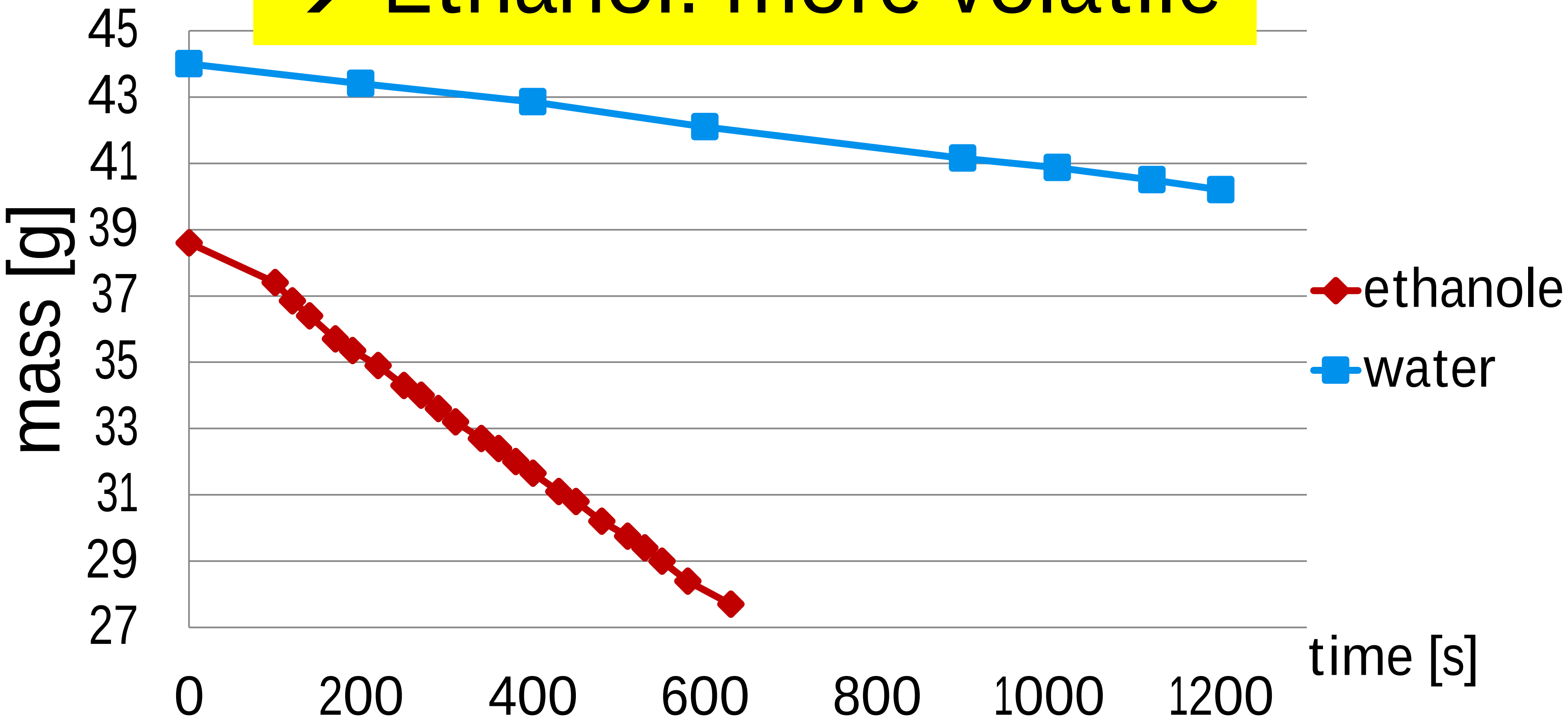
# EXTRA MEASUREMENTS

# Airflow importance

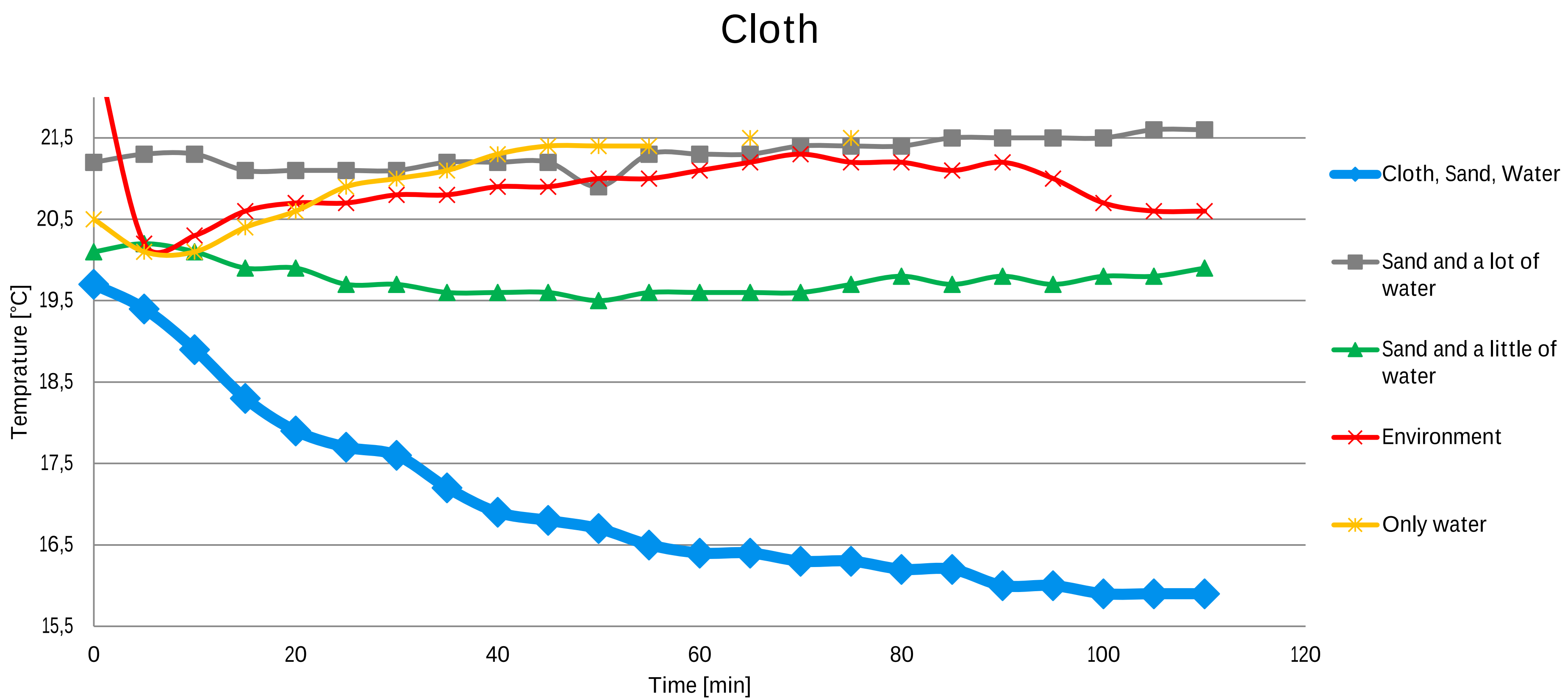



# Water vs. ethanol: Rate of evaporation

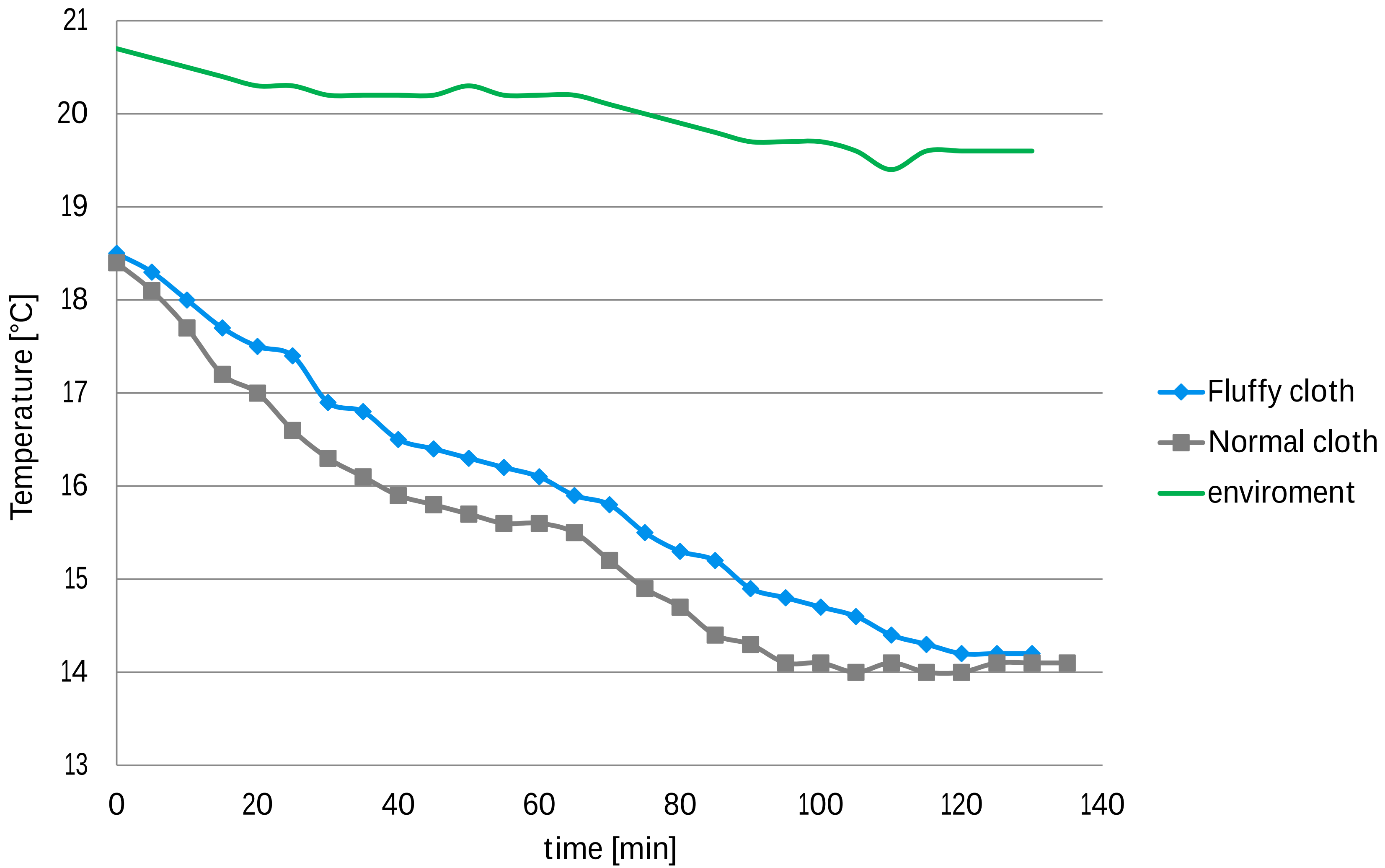
→ Ethanol: more volatile



# Do we need cloth or not?



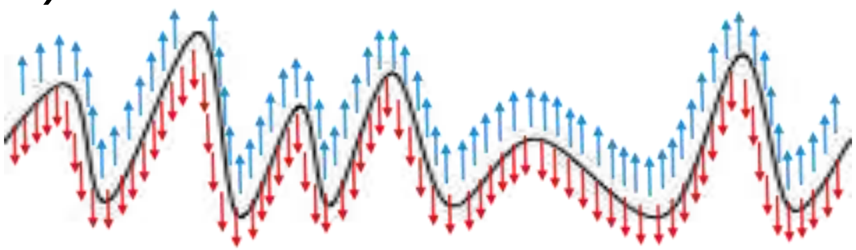
# What is the best material for cloth?



# Why the type of cloth does NOT matter?

1) Water fills gaps

2) Water soaks



- Water fills gaps.
- The surface of water = the area of evaporation

→ The same as normal cloth

Area of evaporation

=

area through which heat gets in

- Equilibrium temperature doesn't change

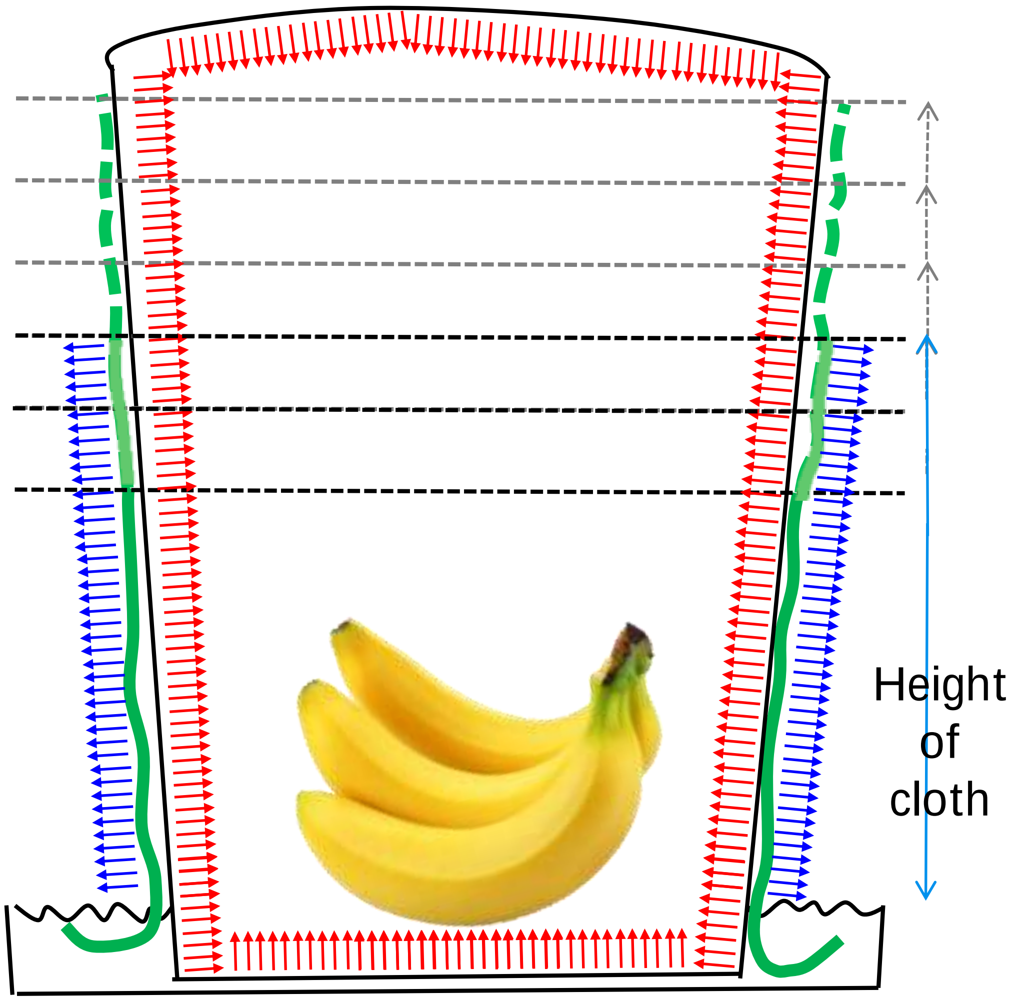
# Effect of different sizes

# Effect of different shapes

# Our refrigerator

$$T = T_{air} - \frac{A\lambda}{B}\left(1 - e^{-\frac{BSv}{C}t}\right)$$

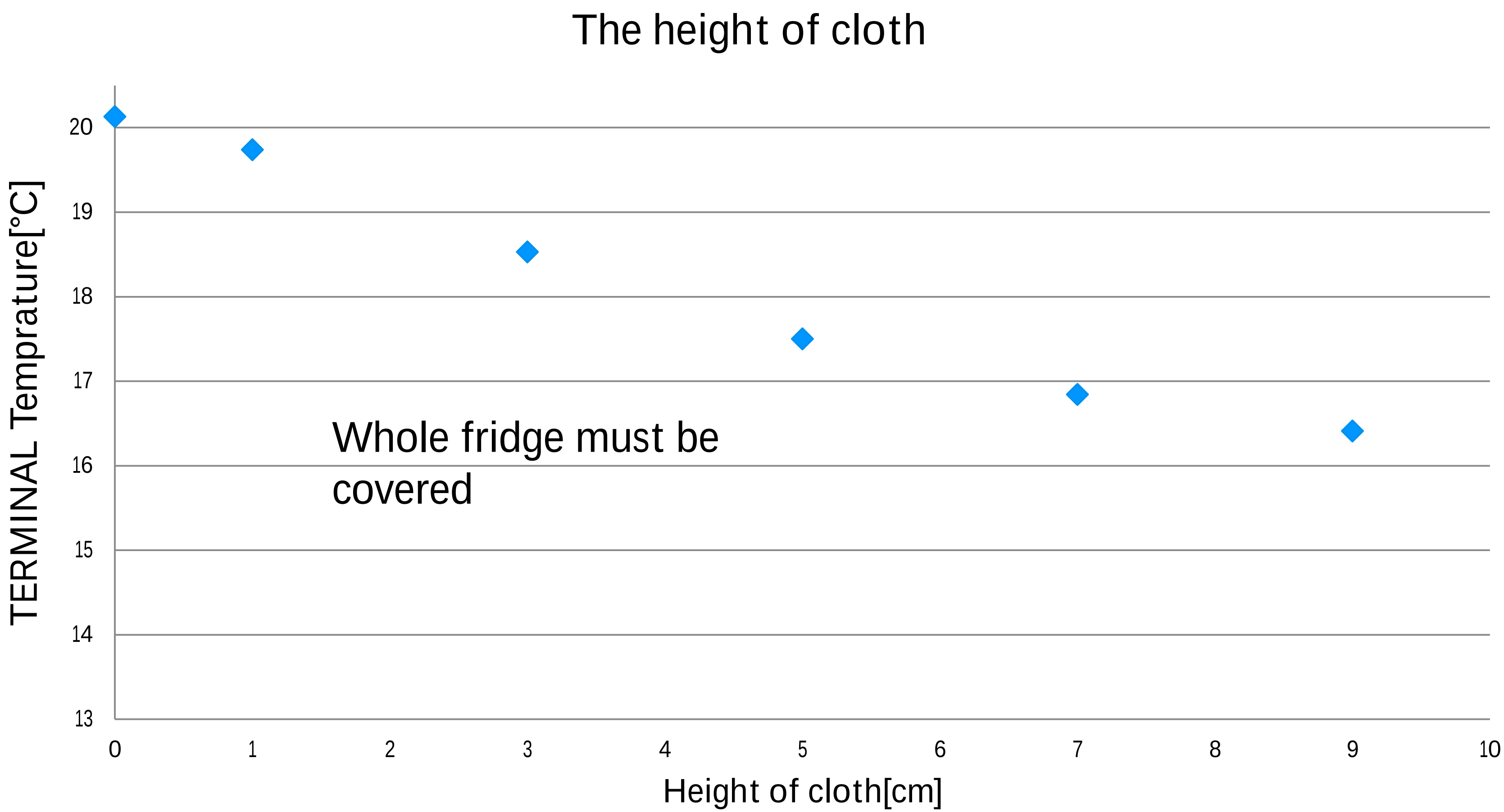
# Covered VS uncovered areas




- Uncovered areas
  → heat gets in
- Covered areas

  → Evaporation + heat gets in

# Does area of cloth matter?



only requirement for fridge's surface

...ISOLATED AREAS MUST BE UNCOVERED WITH CLOTH

So that area of evaporation

=

area trough heat gets in

# Speed of cooling

k1= ability of liquid to evaporate [kg/m3]
k2= part of air which cools down [J/Km3]

$$dm_{water} = k_1 S v dt$$

$$C = m_w c_w + m_{pot} c_{pot} + \ldots = m_{total} c_{eff}$$

$$k_1 S v L_V dt - k_2 S v (T_{air} - T_{fridge}) dt = -C dT$$

$$T = T_{air} - \frac{k_1 L_v}{k_2}\left(1 - e^{-\frac{k_2 S v}{m_{total} c_{eff}} t}\right)$$

Properties of liquid

1/tau

Temperature difference

# Assman psychrometer: theory

Equillibrium
of heat flow:

$$dQ_{transfered} = dQ_{latent}$$

$$dQ_{transfered} = dm_{air} c_{air} \left( T_{air} - T_{fridge} \right)$$

$$dQ_{latent} = dm_{water} L_v$$

Air cools to Tfridge; vapor pressure saturates:

$$dQ_{latent} = \frac{nM\lambda}{p} \left( E\left( T_{fridge} \right) - e \right)$$

$$dQ_{transfered} = nc_p \left( T_{air} - T_{fridge} \right)$$

$$\frac{M_{air}}{p_{atm}} [E(T_{fridgel}) - e_{air}] = c_p (T_{air} - T_{fridge})$$

# Assman psychrometer: theory

Surrounding air:

- Transfers heat to the cloth:

$$dQ_{transfered} = dm_{air} c_{air} \left(T_{air} - T_{fridge}\right)$$

- Absorbs water vapor (heat used for evaporation)

$$dQ_{latent} = dm_{water} L_v$$

Equilibrium (terminal temperature):

$$dQ_{transfered} = dQ_{latent}$$

# Minimal T: theoretical estimation

Terminal temperature:

$$dQ_{latent} = dQ_{transfered}$$

$$dmL_T = dm_{air} c_{air} (T_{air} - T_{fridge})$$

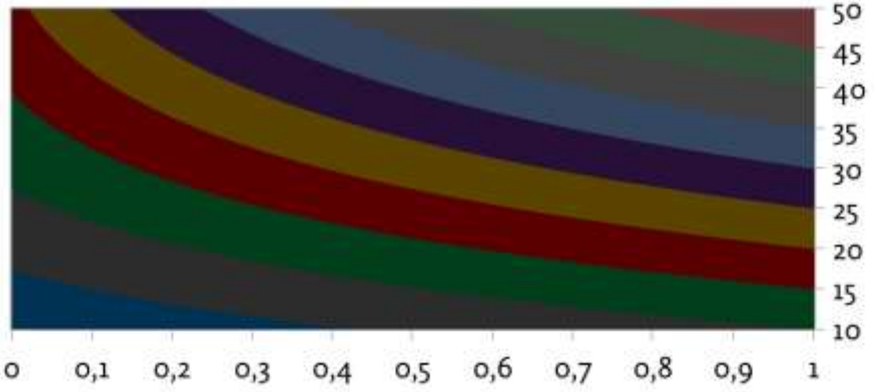
$$\frac{M_{air}}{p_{atm}} [E(T_{fridgel}) - e_{air}] = c_p (T_{air} - T_{fridge})$$

Numerically solved for $T_{fridge}$

(complicated function $E(T)$)

# Conclusion – What should the most effective refrigerator look like?

$$T = T_{air} - \frac{A\lambda}{B}\left(1 - e^{-\frac{BSv}{C}t}\right)$$




- Minimal temperature:
  - sufficient air flow, maximize evaporation area
  - volatile liquid with low concentration in air (eg. Ethanol)
- Fastest cooling:
  - Fast air flow
  - Minimise thermal capacity of the fridge (eg. Low outer pot)
- Prediction of minimal temperature