Evaporation Velocity of Cryogenic Liquid With and Without Spreading

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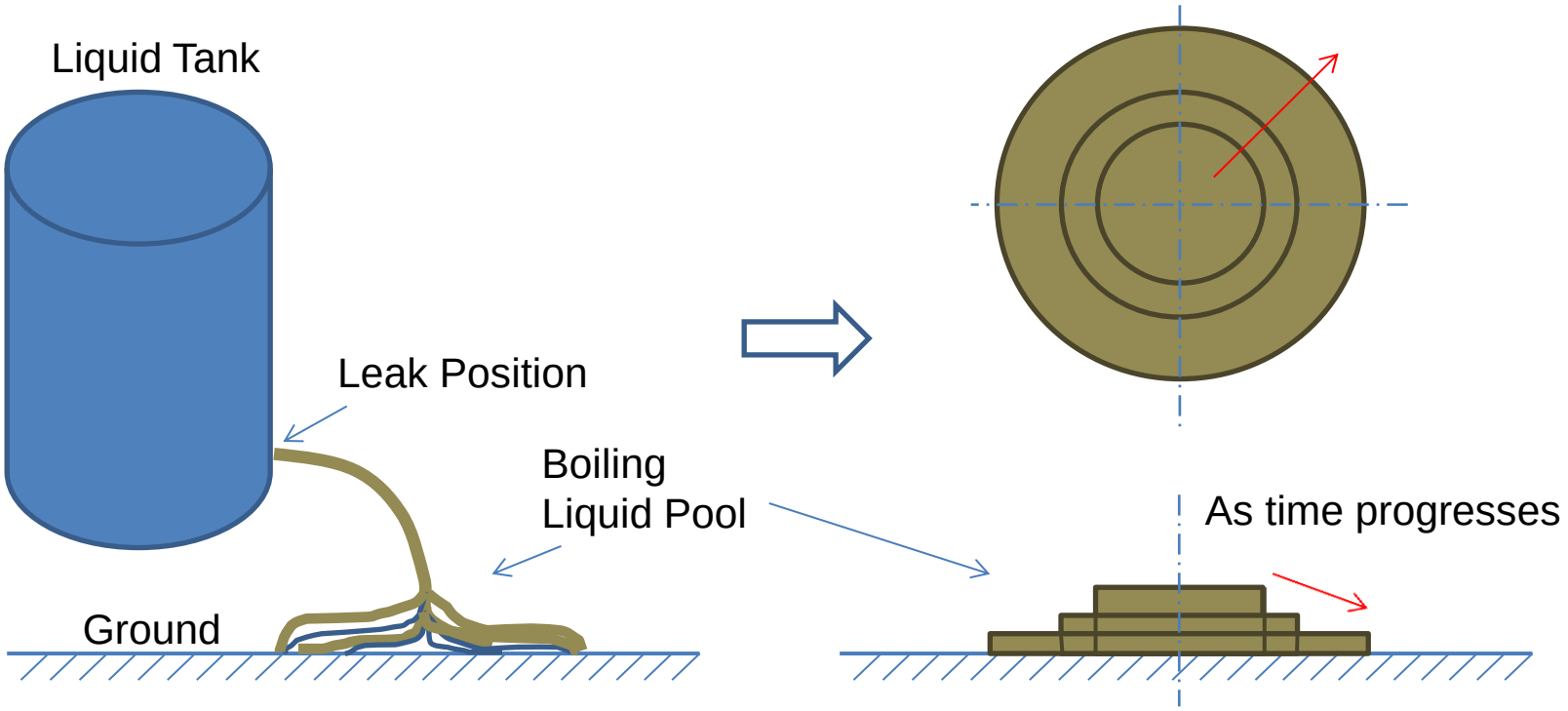
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Introduction(1)

Formation of a Pool and Its Spread



Introduction(2)

Evaporation of A Non-Spreading Pool



Evaporation of A Spreading Pool



Introduction(3)

- **Why Is The Phenomenon Important?**
  - ✓ Fires and explosions in case of LNG, LPG and so on.
  - ✓ Inhalation of toxic material due to dispersion with wind
- **What To Study?**
  - ✓ Measurement of the evaporation velocity
  - ✓ Because it is a key parameter to analyze the spread of liquid
  - ✓ Comparison between experimental results and unsteady 1-dimensional heat conduction model
  - ✓ To suggest a new measurement technique for the evaporation velocity

Introduction(4)

API RP 581 Risk-based Inspection Technology

- Loss Of Containment - Leak
  Occurs only when the pressure boundary is breached.

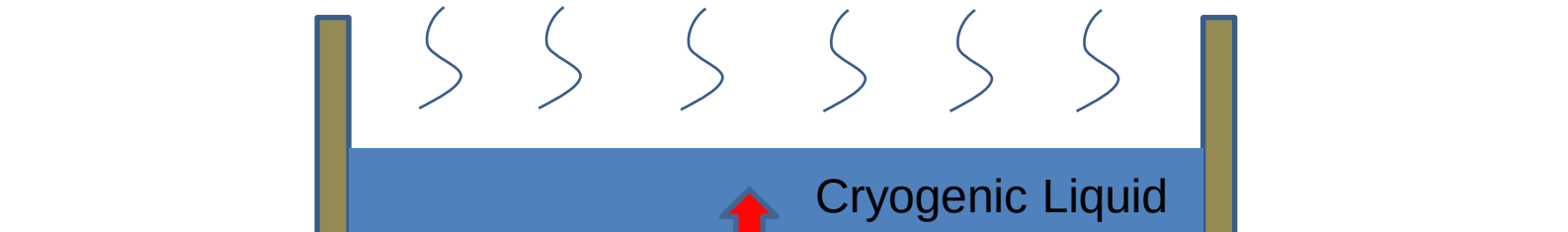
- Continuous Release - Spreading pool
  Occurs over a longer period of time, allowing the fluid to disperse in the shape of an elongated ellipse.

- Instantaneous Release - Non-spreading or Spreading pool
  Occurs so rapidly that the fluid disperses as a single large cloud or pool.

API(American Petroleum Institute)

Evaporation Model(1)

Evaporation of A Non-Spreading Pool



$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

Ground

$T = T_a$ for $0 \le z \le \infty$ at $t = 0$

$T = T_B$ for $0 < t$ at $z = 0$

$T = T_a$ for $0 < t$ at $z = \infty$

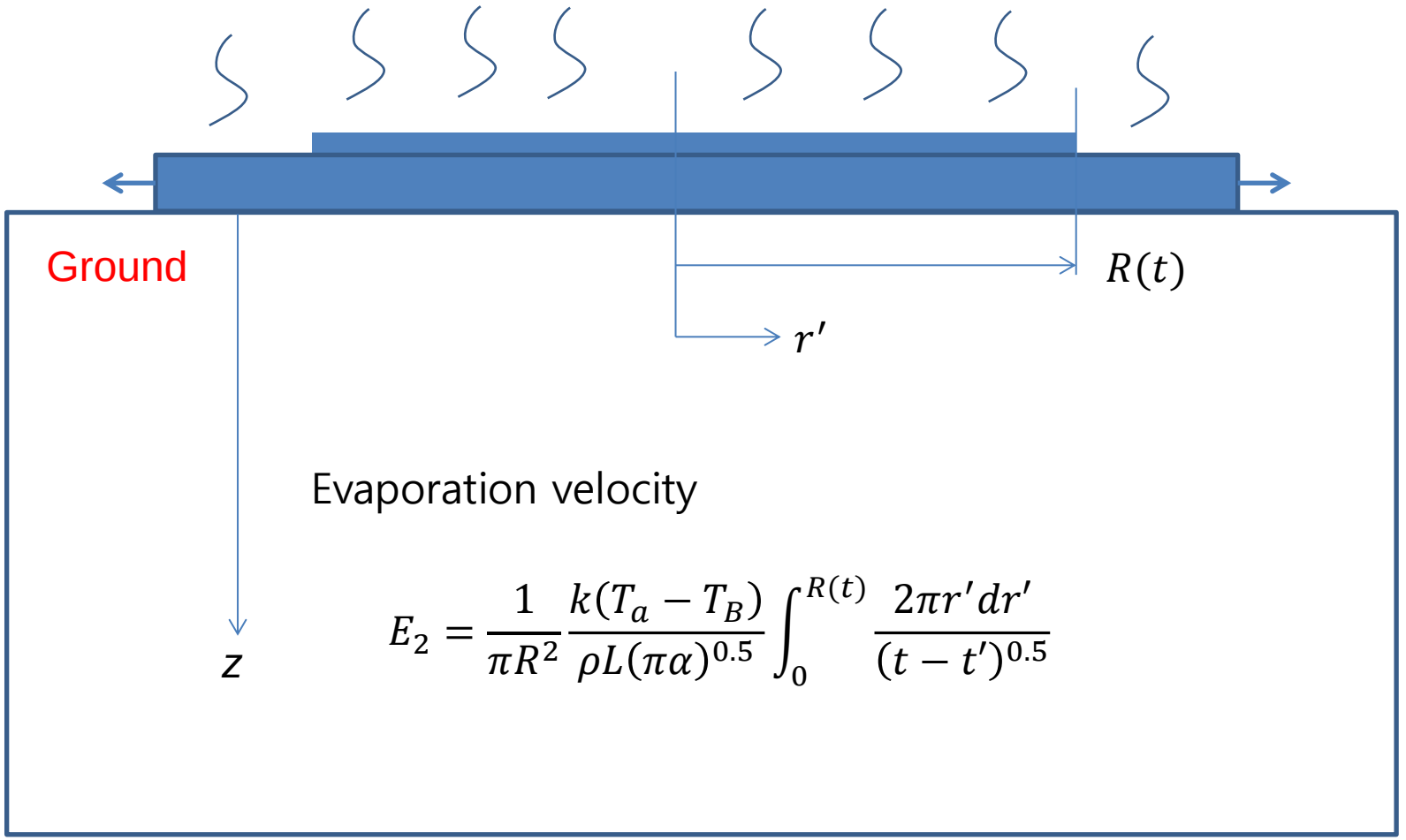
z

Heat flux $q'' = \dfrac{k(T_a - T_B)}{(\pi\alpha)^{0.5}} t^{-0.5}$

Evaporation velocity $E_1 = \dfrac{q''}{\rho L} = \dfrac{k(T_a - T_B)}{\rho L(\pi\alpha)^{0.5}} t^{-0.5}$

Evaporation Model(2)

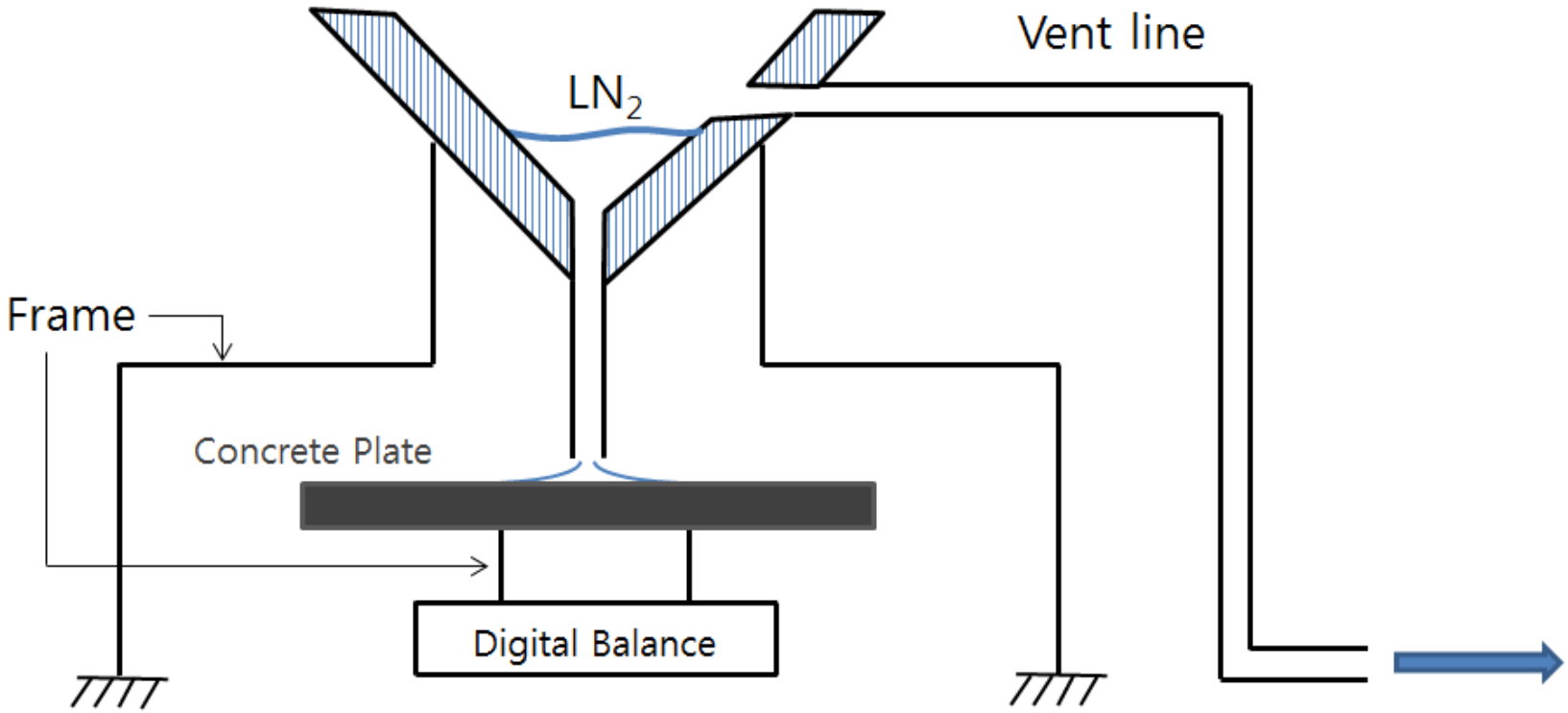
Evaporation of A Spreading Pool



Evaporation velocity

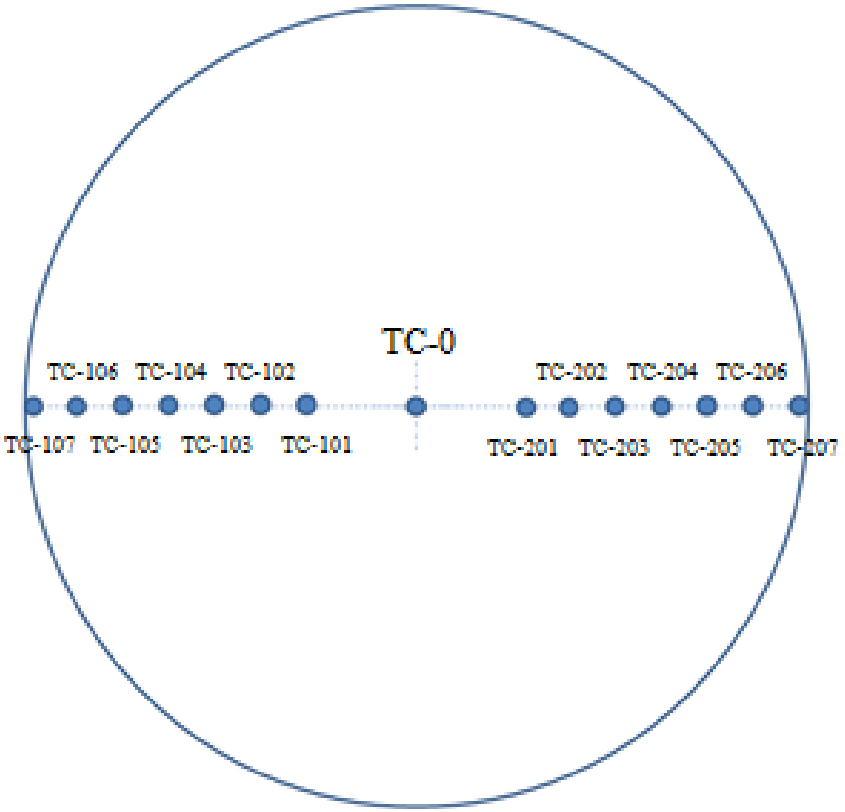
$$E_2 = \frac{1}{\pi R^2} \frac{k(T_a - T_B)}{\rho L(\pi\alpha)^{0.5}} \int_0^{R(t)} \frac{2\pi r' dr'}{(t - t')^{0.5}}$$

Experimental Apparatus(1)



Experimental Apparatus(2)

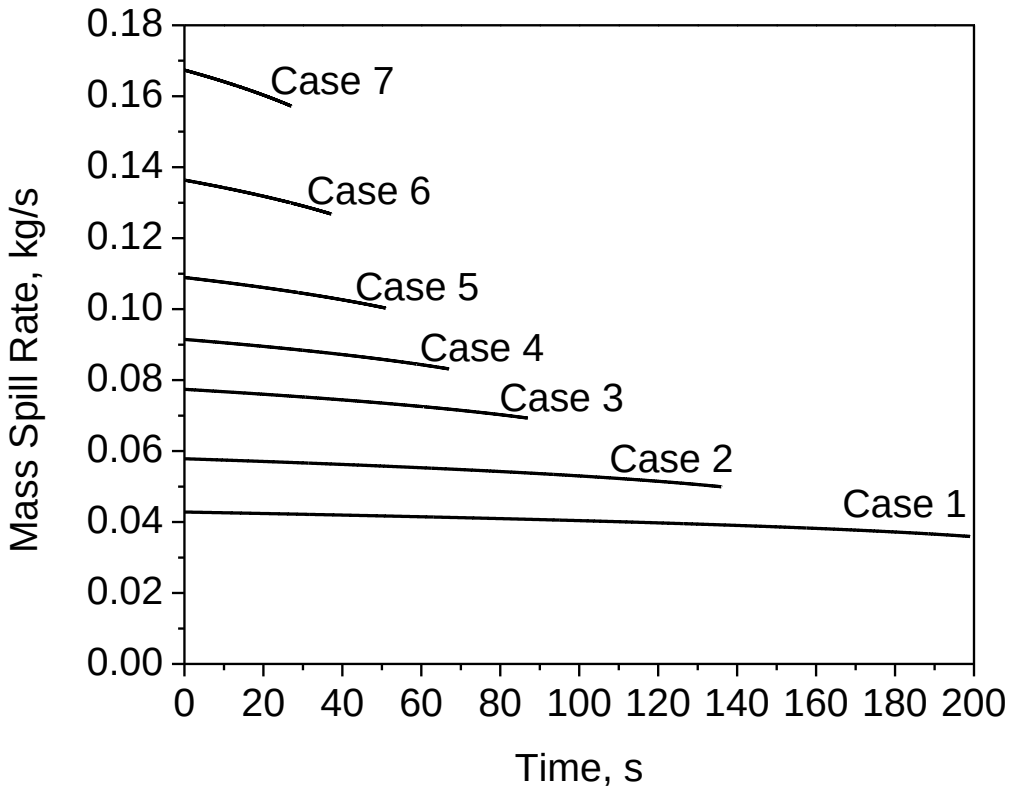
The Concrete Ground



i	Distance from the center of the plate, m	Thermocouple number
0	0	TC-0
1	0.20	TC-101, TC-201
2	0.25	TC-102, TC-202
3	0.30	TC-103, TC-203
4	0.35	TC-104, TC-204
5	0.40	TC-105, TC-205
6	0.45	TC-106, TC-206
7	0.50	TC-107, TC-207

Experimental Apparatus(3)

Spill Rates



Case	Spill time, s	Nominal mass spill rate, kg/s	Nominal volume spill rate, m^3/s
1	198	0.0402	4.9806×10^{-5}
2	135	0.0546	6.7755×10^{-5}
3	87	0.0739	9.1709×10^{-5}
4	67	0.0877	1.0873×10^{-4}
5	51	0.1050	1.3024×10^{-4}
6	37	0.1319	1.6358×10^{-4}
7	27	0.1629	2.0203×10^{-4}

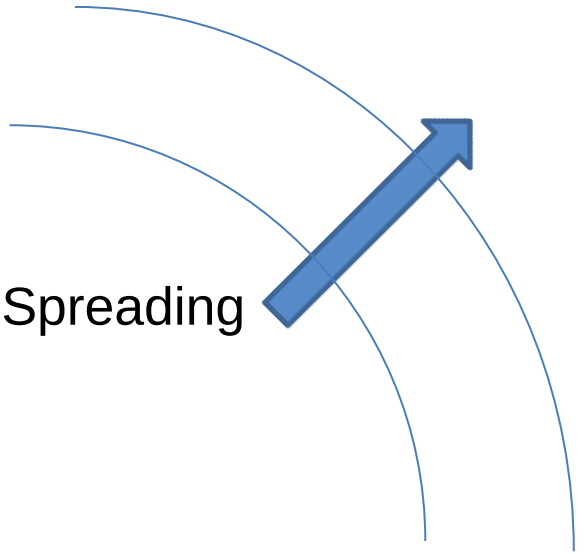
Experimental Apparatus(4)

Evaporation Velocity, E(m/s)

$$W_i + \Delta t \dot{W}_s \gg W_{i+1}$$

$$W_i + \Delta t \dot{W}_s - Evaporation = W_{i+1}$$

$$E = \frac{Evaporation}{\rho A \Delta t}$$



TC location	i	i+1
Time	t_i	t_{i+1}
Mass of LN_2	W_i	W_{i+1}
Spill rate	$\dot{W}_s$	

Experimental Apparatus(5)

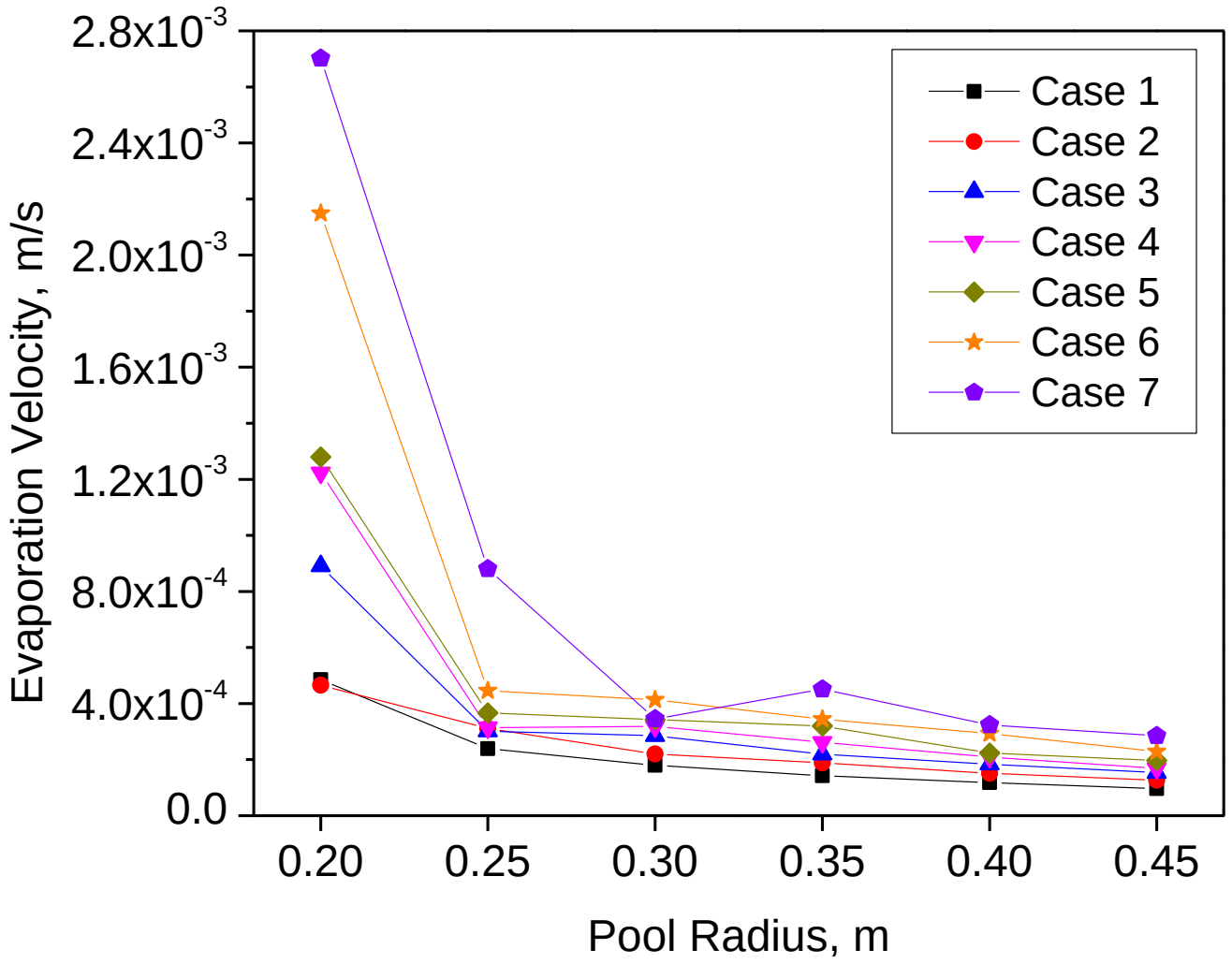
Table 1 Properties of liquid nitrogen

Density, kg/m^3	Latent heat of vaporization, kJ/kg	Kinematic viscosity, m^2/s	Boiling temperature, K
806.11	199.18	1.96×10^{-7}	77

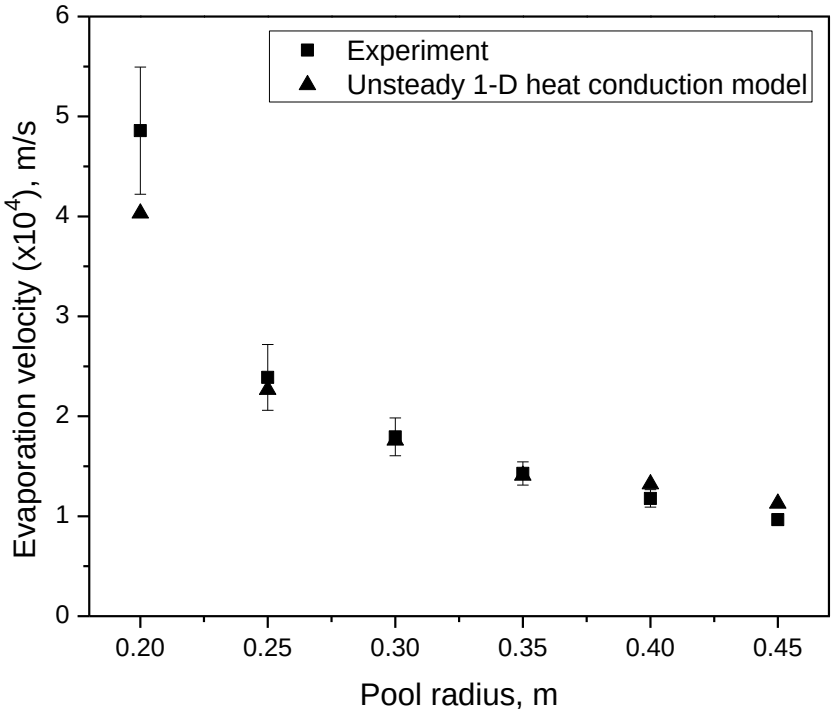
Table 2 Thermal properties and conditions of the plate

Material	Density, kg/m^3	Thermal conductivity, W/m. K	Thermal Diffusivity, m^2/s	Initial temperature, K
Concrete	2300	1.05	$9.5X10^{-7}$	293

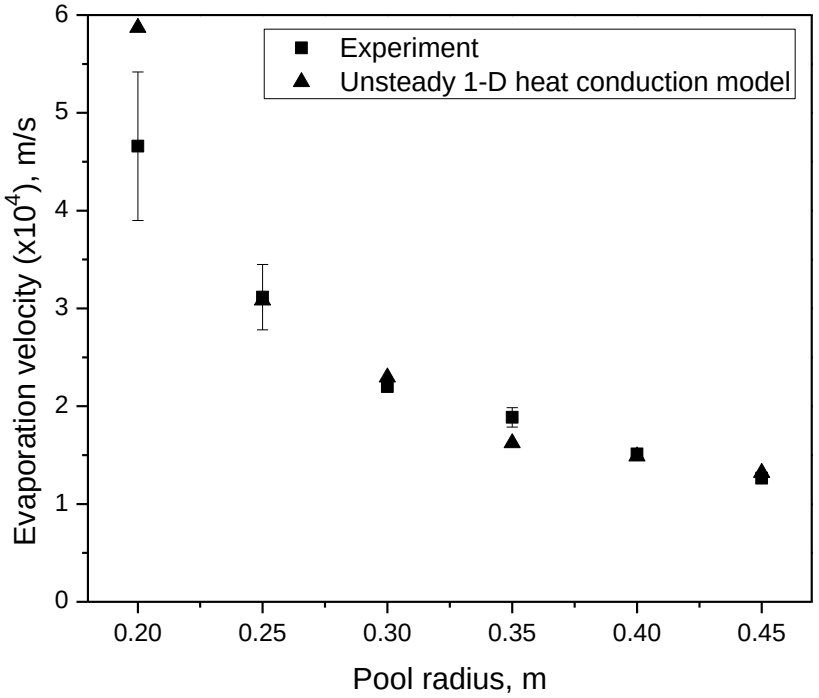
Results & Discussion(1)



Results & Discussion(2)

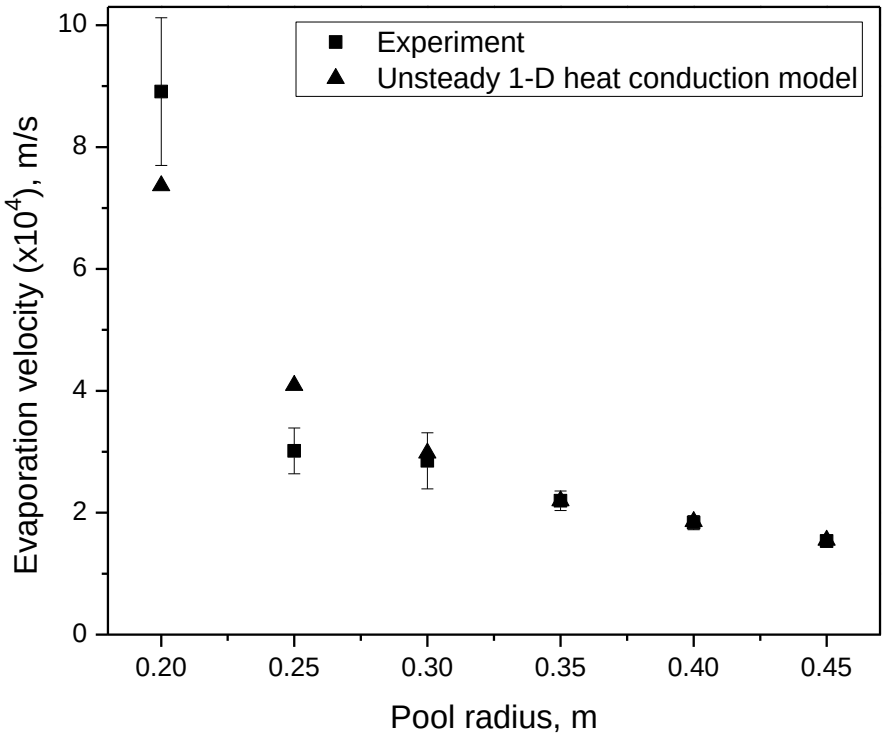


Case 1

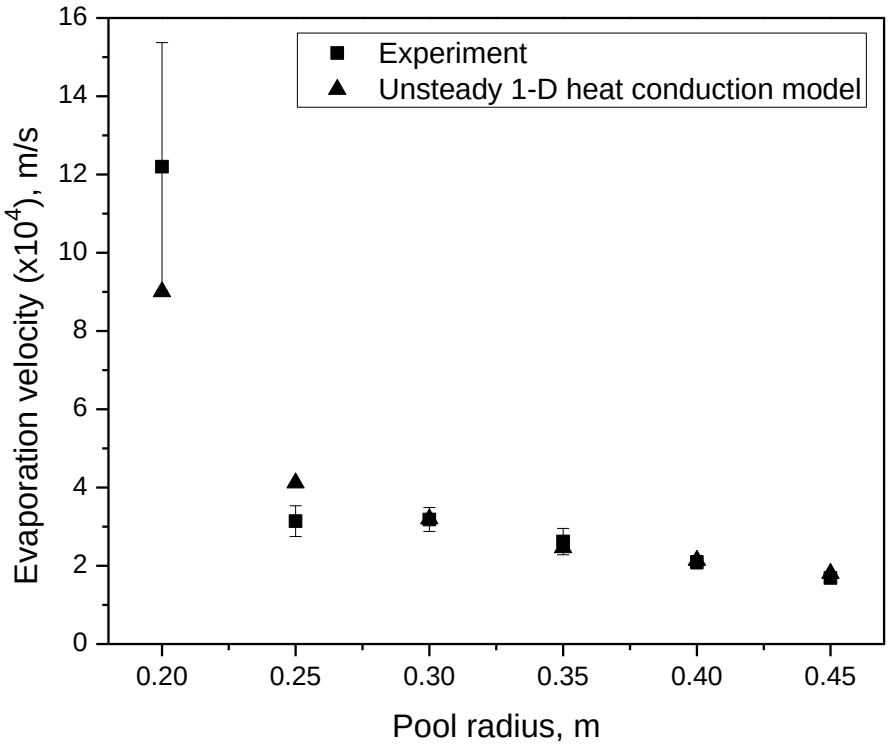


Case 2

Results & Discussion(3)

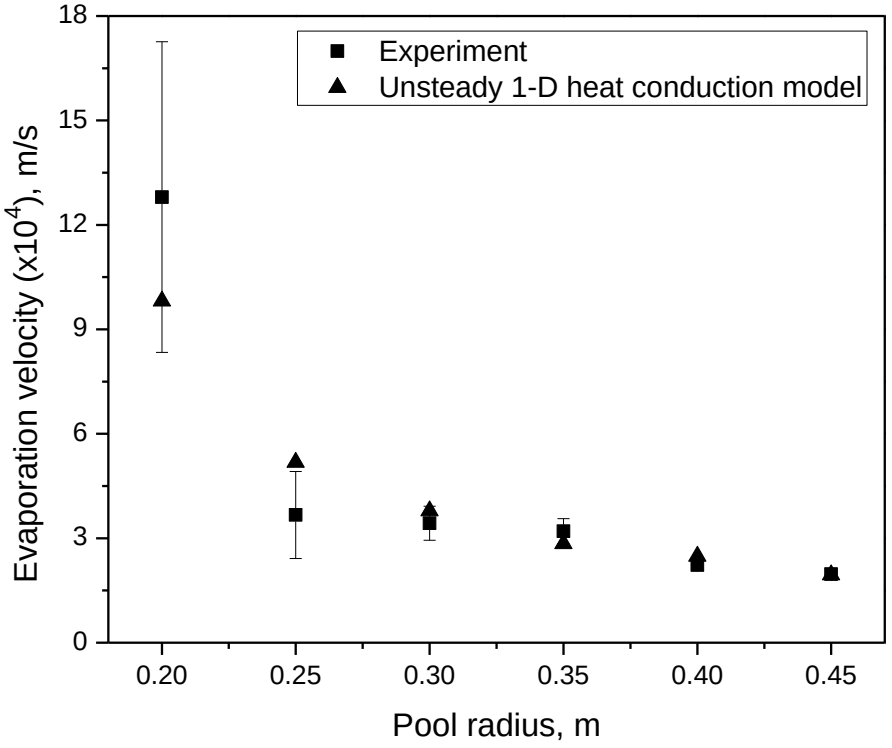


Case 3

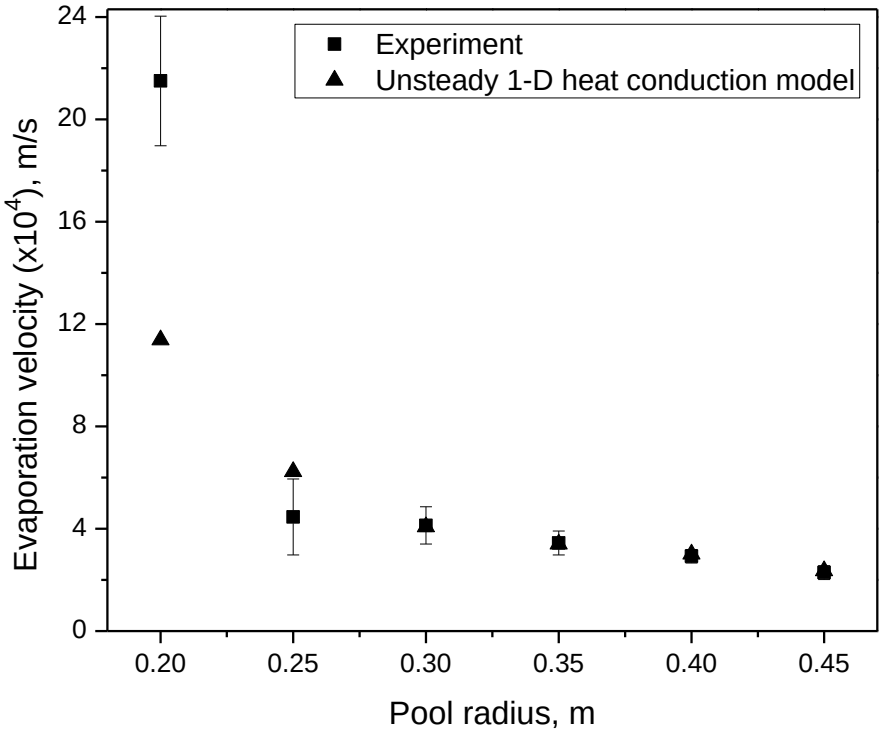


Case 4

Results & Discussion(4)

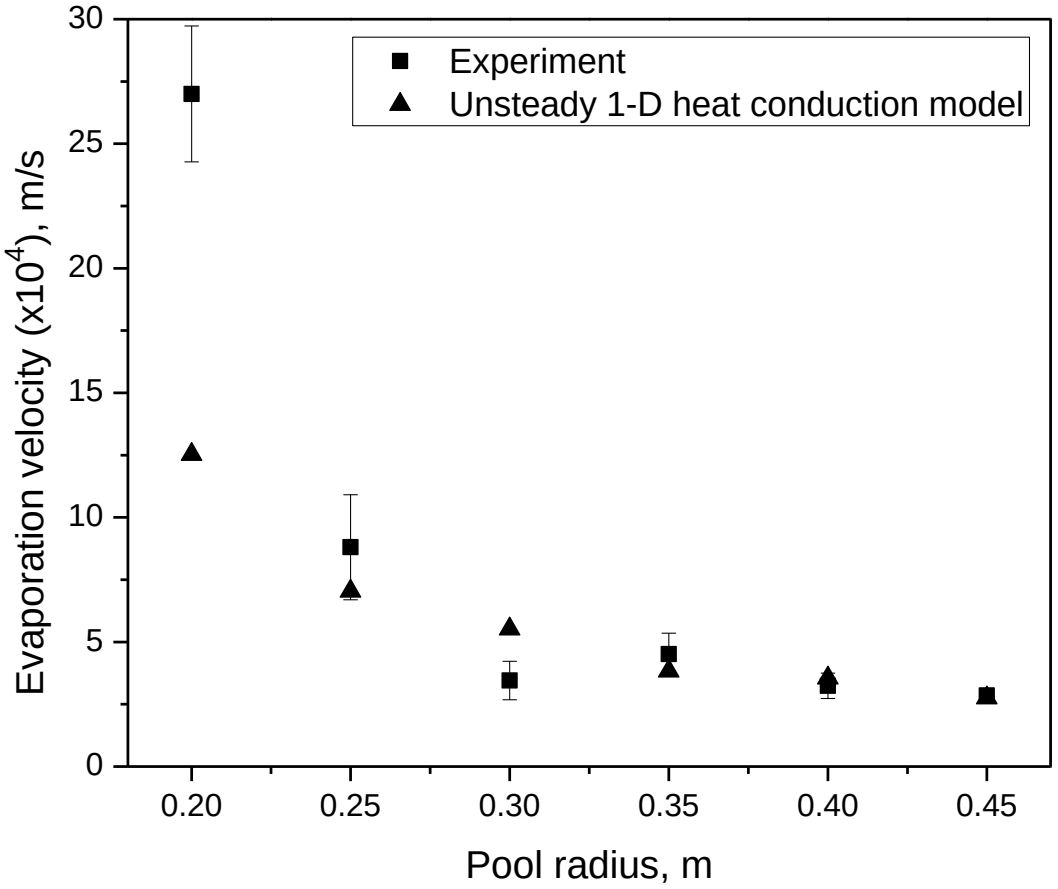


Case 5



Case 6

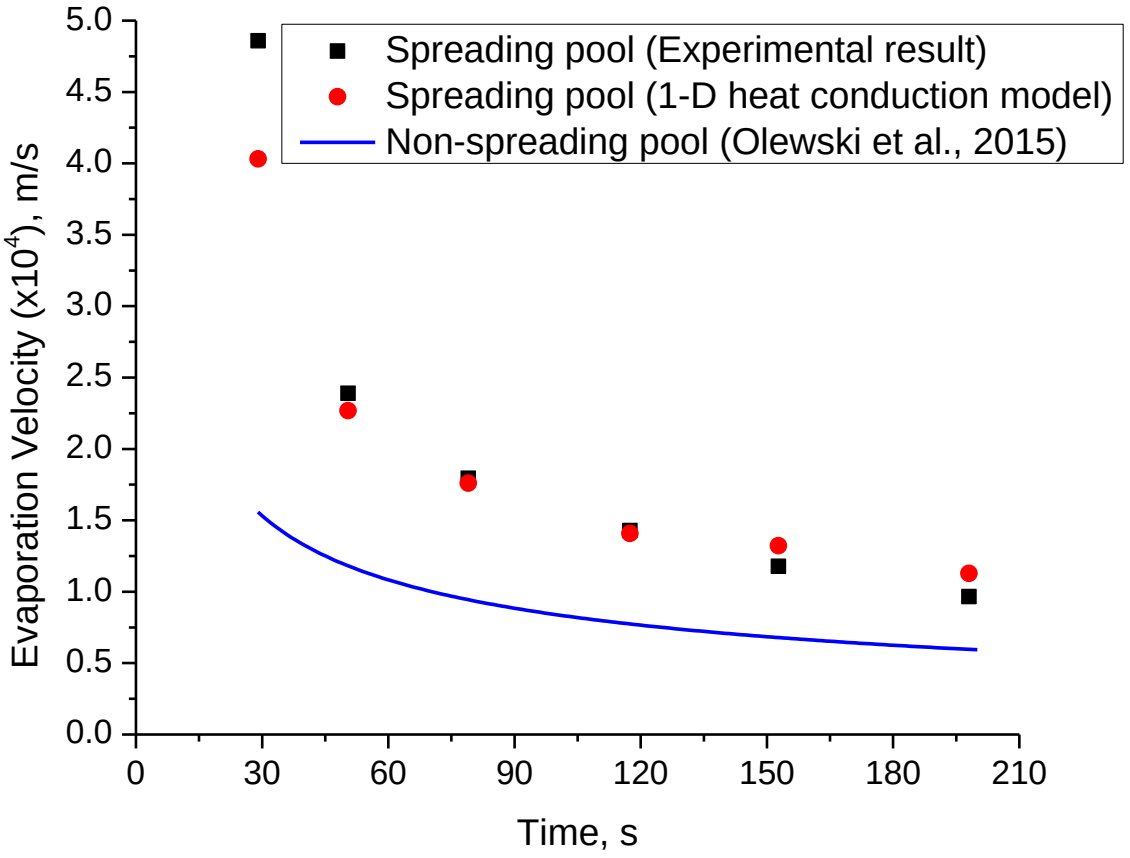
Results & Discussion(5)



Case 7

- Disagreement between the first values
- Discrepancy among the measurement values at 0.2 m.

Results & Discussion(6)



Case 1

Conclusions

- The good agreement between the unsteady 1-D heat conduction model and the experimental data except the initial period.

- A new semi-theoretical method for measuring the evaporation velocity of the spreading pool without providing information about the spill rate and pool mass. We need only experimental data of the pool radius with time. Therefore, we don't need a digital balance as a part of experimental apparatus.

- The evaporation velocities in the spreading pool are much greater than those of the non-spreading pool
  - ✓ because the spreading pool spreads continuously to new warm ground while the non-spreading pool is cooling ground continuously, which leads to decrease of heat flux into the non-spreading pool.