SIMILAR FLUIDS BASED ON THERMAL GRAVITATIONAL SCALING USING DIMENSIONLESS NUMBERS FOR THREE EXAMPLE APPLICATIONS

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ABSTRACT

The performance prediction of thermal systems in reduced gravity environments is of interest when extraterrestrial habitats are designed. However, adequate testing is often not available and the effects of reduced gravity in particular on two-phase flow systems, such as vapor compression cycles, are still poorly understood. One research approach is to design a terrestrial model system such that the extraterrestrial prototype system will be approximated. This research field has received some attention in the past but did not receive much attention recently. This paper presents model systems that are similar to a fictious desired prototype for three case examples. Additionally, the paper lists questions regarding thermal gravitational scaling that are insufficiently answered in the open literature.

NOMENCLATURE

Latin symbols		**Greek symbols**	
c_p	Heat capacity [kJ/(kg·K)]	λ	Thermal conductivity [W/(m·K)]
D	Hydraulic diameter [m]	μ	Viscosity [kg/(m·s)]
G	Gravity [m/s^2]	ν	Kinematic viscosity [m^2/s]
h	Heat transfer coefficient [W/(m^2·K]	ρ	Density [kg/m^3]
h_{fg}	Heat of vaporization [kJ/kg]	σ	Surface tension [N/m]
L	Length [m]	θ	Angle [°]
$\dot{m}$	Mass flow rate [kg/s]		
P	Pressure [kPa]	**Subscripts**	
$\dot{Q}$	Heat transfer rate [W]	f	Liquid
T	Temperature [°C]	g	Gaseous
S	Entropy [kJ/(kg·K)]	m	Model
S	Slip ratio [-]	p	Prototype
U	Velocity [m/s]		
Z	Value of objective function [-]		

INTRODUCTION

The USA, China and the UAE plan to launch rockets towards Mars in 2020 for exploration and technology demonstration purposes. The three efforts are symptomatic for an unmissable acceleration of space exploration, both driven by governmental agencies as well as private companies. The far goals are diverse, but some of them are related to sustained human presence in microgravity (space stations) or reduced gravity (human habitats on other planets). The different gravity levels lead to design questions for thermal systems, which often require experiments in relevant environments. Since gravity cannot be shielded against, these experiments are costly and require preparatory work far exceeding the effort for similar experiments in a terrestrial laboratory.

The late 1980s and 1990s gave rise to the research area of *thermal gravitational scaling*, which was supposed to reduce the required testing in micro- or reduced gravity. The applications of the research were thermal systems and the objective was to confidently design a system for micro- or reduced gravity by building a scaled version of the system on earth. In particular, the research focused on scaling laws. Example applications covered both single-phase and two-phase systems and included but were not limited to:

- Single-phase cooling/heating loops
- Heat pipes
- Mechanically pumped two-phase loops in radiator systems
- Capillary force driven two-phase loops
- Two-phase cooling systems for refrigeration and air-conditioning

The most common nomenclature is to label the system that should operate in a non-normal gravity environment the *prototype* and the system that should approximate it on earth the *model* (albeit being a physical system and not merely a computational model).

There is overlap between *thermal gravitational scaling* and *gravity independence*, but the two should not be confused. Obeying gravity independence laws as for example proposed in Zhang et al. (2004) and Bower and Klausner (2006) makes a thermal system gravity independent such that it could be moved into another gravity environment and operate with the same performance at steady-state (transient aspects are rarely included in gravity independence considerations). In contrast, thermal gravitational scaling involves two different systems, where one is a scaled version of the other and approximates its behavior in an environment of different gravity level.

Despite the efforts in the 1990s, there is a shortage of practical scaling laws. As an example, Figure 1 shows a schematic of a standard four component vapor compression cycle and its depiction in a T-s diagram. The main question is how to scale the components and connecting piping and select a fluid such that the (physical) model on earth approximates the prototype on a different planet. Although a clear law has not been established, significant work was conducted (Crowley and Izenson, 1989; Crowley and Sam, 1991; Delil, 2001, 1989, 1991; Hurlbert, 2000; Hurlbert et al., 2004; Ungar, 1998). This study introduces the work of Delil and shows thermal gravitational scaling using three example cases. The goal is to recall past efforts, ask unanswered questions and thereby probe for interest in thermal gravitational scaling 20 years after initial efforts were noticeably reduced.

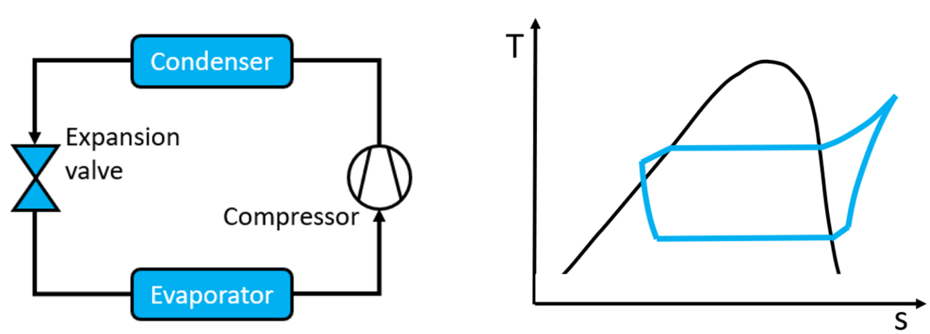

Figure 1: Schematic of four component vapor compression cycle and depiction in T-s diagram.

BRIEF REVIEW OF DELIL'S WORK

Delil has published numerous research studies on the topic of thermal gravitational scaling and presented a scaling approach based on dimensionless numbers. Delil provided the following definition: "…*scaling space-oriented two-phase heat transport systems and system components is the development of reliable spacecraft systems of which the proper in-orbit performance can be predicted using results of experiments with scale models under terrestrial gravity conditions*". He frequently motivated his research with three reasons (Delil, 1989):

- *"For a better understanding of two-phase flow and heat transfer phenomena"*
- *"To provide means for the comparison and generalization of data"*
- *"To develop a useful tool for the design of two-phase flow systems and system components, in order to save money and to reduce costs "*

Delil defined a well-scaled, single-phase flow model as one where the "*velocity, temperature and pressure field are identical*" to the corresponding ones of the prototype. He stated that "e*ven in single-phase systems, scaling is an all but simple problem*" and that "*scaling two-phase systems is considerably more complicated*".

Delil saw the main applications in space exploration but also envisioned his theory to be useful for hyper gravity like on aircraft. His scaling approach and some aspects to be critiqued are described in the following.

Approach

Delil derived dimensionless numbers that describe single and two-phase flow and called them π-numbers, most of which are well known. Table 1 shows the definition and meaning of the π-numbers with small adjustments to $\pi_3, \pi_{14}, \pi_{15}$ and π_{17} as explained in the following section. He started with $\pi_1 - \pi_5$ to cover adiabatic single-phase flow. $\pi_6 - \pi_9$ are gas-liquid property ratios and the Weber number to cover adiabatic two-phase flow. $\pi_{10} - \pi_{14}$ add heat transfer properties. π_{15} was added as especially useful for scaling two-phase flow with respect to gravity (Delil, 1989) and π_{16} for compressibility effects. A detailed reasoning for π_{17} and π_{18} was not provided. Delil presented the numbers with an indication of the types of flow that they are *related* to but did not clearly outline which of them are *essential* for scaling. This is important since Delil said "*perfect similitude between model and prototype is obtained if […] all dimensionless numbers are identical in prototype and model* [which] *is not possible in the case of two-phase flow and heat transfer*". If scaling with respect to all related dimensionless numbers is not possible, it follows that a selection is needed. Delil indeed showed scaling examples for two-phase flow using only the Morton number, but a generalized guide to determining dimensionless numbers essential for scaling could not be found.

The column "Use" in Table 1 indicates the π-numbers that are in the objective function for the examples in this study.

Critique

Delil's work cannot be readily applied because the groups of dimensionless numbers that have to be matched for a certain component (heat pipe, evaporator, etc.) are undefined. It is evident that all related numbers cannot be matched so that either a subgroup of the related numbers must be defined as essential or a deviation of dimensionless numbers between model and prototype must be defined as tolerable.

Additionally, the following points may be helpful for other researchers reading Delil's work and were employed in correcting/reformulating the π-number definitions in Table 1.

- The Boiling number (π_{14}) is usually more intuitively defined as a ratio of heat transfer and capacitance *rates* than as a ratio of enthalpy differences.
- The typical Morton number (π_{15}) definition (Pfister and Hager, 2014) is the inverse of the definition that Delil proposed.
- If the Froude number (π_3) is defined as in Delil's original work, then it is incorrect in the Morton number definition as $Mo = We^3/(Re^4 Fr^2)$.
- The condensation number (π_{17}) is defined incorrectly in several of Delil's publications.

Table 1: 18 π-numbers as proposed by [] and use in objective function for reference cases a), b) and c).

π - number	Meaning	Use	π - number	Meaning	Use
$\pi_1 = \frac{D}{L}$	Geometry		$\pi_{10} = Pr_f = \left(\frac{\mu C_p}{\lambda}\right)_f$	Liquid Prandtl number	
$\pi_2 = Re_f = \left(\frac{\rho u D}{\mu}\right)_f$	Inertia/viscous	a)/c)	$\pi_{11} = Nu_f = \left(\frac{hD}{\lambda}\right)_f$	Convective/conductive	
$\pi_3 = Fr_f = \left(\frac{u}{\sqrt{gD}}\right)_f$	Inertia/gravity	a)/c)	$\pi_{12} = \frac{\lambda_g}{\lambda_f}$	Conductivity ratio	
$\pi_4 = Eu_f = \left(\frac{\Delta P}{\rho u^2}\right)_f$	Pressure head/inertia	c)	$\pi_{13} = \frac{C_{p,g}}{C_{p,f}}$	Specific heat ratio	
$\pi_5 = \cos(\theta)$	Orientation with respect to g		$\pi_{14} = \frac{\dot{Q}}{\dot{m} h_{fg}}$	Rate of quality change	c)
$\pi_6 = S = \frac{u_g}{u_f}$	Slip factor		$\pi_{15} = Mo_f = \frac{We_f^3}{Re_f^4 Fr_f^2} = \frac{\mu_f^4 g}{\rho_f \sigma^3}$	Capillarity/buoyancy	b)
$\pi_7 = \frac{\rho_g}{\rho_f}$	Density ratio	c)	$\pi_{16} = Ma = u/\sqrt{\left(\frac{\partial P}{\partial \rho}\right)_s}$	Mach number	
$\pi_8 = \frac{\mu_g}{\mu_f}$	Viscosity ratio	c)	$\pi_{17} = \frac{h}{\lambda_f}\left(\frac{\mu_f^2}{g \rho_f^2}\right)^{1/3}$	Condensation number	
$\pi_9 = We_f = \left(\frac{\rho u^2 D}{\sigma}\right)_f$	Inertia/surface tension	c)	$\pi_{18} = \frac{L^3 \rho_f^2 g h_{fg}}{\lambda_f \mu_f (T - T_o)}$	Vertical wall condensation number	

EXAMPLE CASES

To illustrate the application of the dimensionless number-based scaling approach, three examples are introduced which could be of interest in an extraterrestrial habitat. The cases are distinguished by both their respective parameters as well as their objective function for optimization. All prototype parameters are shown in Table 2 and individual case descriptions are provided in the following sections.

Table 2: Prototype parameters, iteration variables and objective function for three reference cases.

Case	Fluid	T [°C]	P [kPa]	D [m]	u [m/s]	g	Variables	Z
a)	Water	20	100	0.500	0.10	Moon	$Fluid, T_m, P_m, u$	$obf(\pi_2, \pi_3)$
b)	R134a	0	$P_{sat}(T)$	0.010	0.01	Mars	$Fluid, T_m$	$obf(\pi_{15})$
c)	R600a	40	$P_{sat}(T)$	0.005	0.01	Mars	$Fluid, T_m, D_m, L_m, u_m, q''_m$	$obf(\pi_2, \pi_3, \pi_4, \pi_7, \pi_8, \pi_9, \pi_{14})$

Case A: Adiabatic single-phase flow on Moon

The first fictious reference case is a sewer system on the Moon (g = 1.62 m/s^2) approximated as shown in Figure 2. Water with an open surface flows through a channel with rectangular cross-sectional area where the height is the characteristic length. For such a flow, the Reynolds number is a measure for the turbulence of the flow while the Froude number classifies the flow in a sewer as subcritical/tranquil for Fr<1 or supercritical/shooting Fr>1. This can be relevant for accurate measurements using flow sensors

(Enfinger and Stevens, 2006). The water in the prototype sewer should flow at 100 kPa ambient pressure and with a temperature of 20°C. The height of the water is 0.5 m during normal operation and the flow velocity is 0.1 m/s. The goal is to experimentally simulate the flow on earth looking at the Reynolds and Froude number in a channel with equal height of the flow by selecting a fluid and adjusting the temperature and pressure as needed.

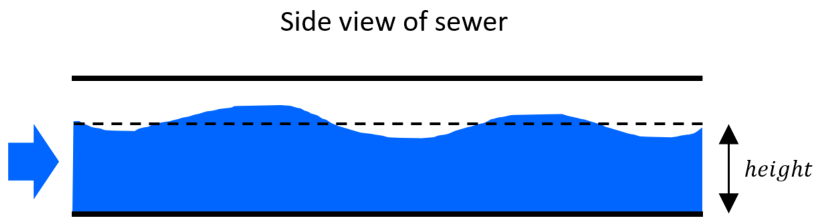

Figure 2: Sketch of sewer for example Case A.

Case B: Adiabatic two-phase flow scaled by Morton number

Two-phase R134a should flow adiabatically at a temperature of 0°C through a pipe of 1 cm in diameter and with a saturated liquid velocity of 1 cm/s on Mars (g = 3.71 m/s^2). This is to be approximated at earth gravity leveraging the Morton number (π_{15}) as described by Delil in several research articles. Using this example, it will be shown that matching the Morton number is straight forward but that despite a good match of the Morton number, other dimensionless parameters can deviate significantly.

Case C: Condensing two-phase flow scaled by multiple π-numbers

A system is designed for Mars in which two-phase R600a rejects heat at a saturation temperature of 40°C. The refrigerant should flow in a small pipe of 0.5 cm in diameter with a saturated liquid velocity of 0.01 m/s. A physical terrestrial model should be built. It is assumed that convection clearly overrules conduction effects in the condensation process such that $\pi_{10} = Pr_f, \pi_{11} = Nu_f$ and $\pi_{12} = \lambda_g/\lambda_f$ can be disregarded. Matching is pursued for the liquid phase $\pi_2 = Re_f, \pi_3 = Fr_f, \pi_4 = Eu_f$ and $\pi_9 = We_f$ as well as the gas to liquid ratios $\pi_7 = \rho_g/\rho_f$ and $\pi_8 = \mu_g/\mu_f$. Additionally, the model should approximate the ratio of the heat transfer rate to the heat capacitance flow of the refrigerant $\pi_{14} = \dot{Q}/(\dot{m}h_{fg})$.

FORMULATION OF OPTIMIZATION PROBLEM

Each presented case is solved by matching certain dimensionless numbers. To apply an optimization algorithm, these numbers must be framed in an objective function (or cost function). The objective function together with iteration variables and variable bounds is then the optimization problem. The objective function is chosen to be intuitive such that the results can be readily interpreted. For one dimensionless π-number in the objective function, the deviation from the prototype π-number is calculated relative to the prototype π-number. The value of 1 is subtracted to make the ideal value of the cost function 0.

$$Z = obf(\pi_1) = \frac{\pi_{1,m} - \pi_{1,p}}{\pi_{1,p}} - 1 = \frac{\pi_{1,m}}{\pi_{1,p}} - 1 \quad (1)$$

If the cost function contains several π-numbers, then the average of their deviations is calculated and constitutes the final cost function:

$$Z = obf(\pi_1, \pi_2, \dots, \pi_n) = \frac{1}{n}\left\{ \left|\frac{\pi_{1,m}}{\pi_{1,p}} - 1\right| + \left|\frac{\pi_{2,m}}{\pi_{2,p}} - 1\right| + \cdots + \left|\frac{\pi_{n,m}}{\pi_{n,p}} - 1\right| \right\}. \quad (2)$$

For each contributing π-number, the absolute value is computed for the summation such that positive and negative deviations cannot cancel out. Therefore, a value of the objective function of Z=0.2 means that the π-numbers in the model deviate on average 20% from the respective π-number in the prototype.

The software EES (Klein and Alvarado, 2002) with the inbuilt *Conjugate Directions Method* was used to generate results for the following examples. The iteration variables and objective functions for each case are listed in Table 2. The bounds and initial values for the iteration variables are shown in Table 3. The optimization was conducted for an arbitrary selection of 12 fluids as shown in Table 4 for the three case examples.

Table 3: Bounds and initial values for iteration variables.

Variable	Lower	Guess	Upper
D_m $[m]$	0.001	0.005	1
T_m $[°C]$	-40	5	100
P_m [kPa]	30	500	2000
u_m $[m/s]$	0.001	0.2	10

Table 4: Considered fluids for each case example.

Acetone	Ethanol	Propane	R143a
Ammonia	Methanol	R113	R152a
Water	n-Octane	R134a	R600a

RESULTS

Case A: Adiabatic single-phase flow on Moon

This optimization problem can be simplified analytically by first evaluating the Froude number condition

$$Fr_{f,p} = Fr_{f,m} \quad (3)$$

$$\left(\frac{u}{\sqrt{gD}}\right)_{f,p} = \left(\frac{u}{\sqrt{gD}}\right)_{f,m}. \quad (4)$$

Realizing that the diameter shall be equal in this example, it follows that the flow velocity must be

$$u_m = u_p \sqrt{\frac{g_m}{g_p}}. \quad (5)$$

The Reynolds number condition with fixed diameter and known velocity then reduces as follows:

$$Re_p = Re_m, \quad (6)$$

$$\left(\frac{uD}{\nu}\right)_{f,p} = \left(\frac{uD}{\nu}\right)_{f,m}, \quad (7)$$

$$\nu_{f,p}(T_p, P_p) = \nu_{f,m}(T_m, P_m) \cdot \sqrt{\frac{g_p}{g_m}}. \quad (8)$$

It remains to search the suitable (T_m, P_m) combination that matches the kinematic viscosities respecting the gravity adjustment. There is a perfect match (Z=9.6e-9) for ethanol at -5.75°C as shown in detail in Table 5. The pressure is insignificant for the viscosity such that the optimization of the pressure is almost meaningless and the result is close to the initial guess value. The objective value Z would change negligibly if the pressure of the model was changed to 100 kPa (although the result is 500.7 kPa). For all other fluids, the optimization was constrained by the imposed bounds and the objective value larger than for ethanol.

Table 5: Results for Case A.

Information	Prototype	Model
Fluid [-]	Water	Ethanol
Flow velocity [m/s]	0.1	0.246
Temperature [°C]	20	-5.73
Pressure [kPa]	100	501
Density [kg/m³]	998.2	812
Viscosity [kg/(m·s)]	0.001002	0.002004
$\pi_2 = Re_f$	49830	49830
$\pi_3 = Fr_f$	0.1111	0.1111
Z [-]	9.631e-9	

Case B: Adiabatic two-phase flow scaled by Morton number

The Morton number is defined as follows:

$$\pi_{15} = Mo_f = \frac{We_f^3}{Re_f^4 Fr_f^2} = \frac{\mu_f^4 g}{\rho_f \sigma^3} \tag{9}$$

The combination of dimensionless numbers cancels out the pipe diameter and the flow velocity. Hence, if the gravity level is set by the problem statement, matching the Morton number becomes a search for a saturation temperature that solves the following equation:

$$\left(\frac{\mu_f^4}{\rho_f \sigma^3}\right)_{f,m} = \frac{g_p}{g_m}\left(\frac{\mu_f^4}{\rho_f \sigma^3}\right)_{f,p}. \tag{10}$$

The first row in Table 6 shows the prototype parameters and results for the four π-numbers of interest in this example: Re_f, Fr_f, We_f and Mo_f. The other rows show results for the models sorted by the best match. In the optimization process, Fr_p and Fr_m were equalized using the flow velocity u, which does not affect the Morton number. This explains the perfect match of all Froude numbers in Table 6. Model 1 through 5 have very good objective values (matches of the Morton number). However, the Morton number alone is a poor indicator of the similarity of two-phase flows. Model 4 and 5 in Table 6 show that although the Morton numbers match, the Reynolds and Weber number differ significantly. Additionally, the liquid-gaseous property ratios differ strongly, such that prototype and model are not properly scaled.

Table 6: Results for Case B.

Order	Fluid	T [°C]	$\pi_2 = Re_f$	$\pi_3 = Fr_f$	$\pi_9 = We_f$	$\pi_{15} = Mo_f$	Z
Prototype	R134a	0.00	487.6	0.05192	0.1133	9.551E-12	0
1. Model	Acetone	25.31	415.3	0.05192	0.0915	9.551E-12	0.000002118
2. Model	R152a	3.40	743.0	0.05192	0.1987	9.551E-12	0.000002623
3. Model	R600a	23.50	588.2	0.05192	0.1455	9.551E-12	0.000005617
4. Model	Propane	49.15	974.9	0.05192	0.2854	9.551E-12	0.000040310
5. Model	CO2	-5.88	1420.0	0.05192	0.4712	9.551E-12	0.000040800

Repeated execution of the optimization algorithm for this case example shows slight variations in the dimensionless numbers and the Z-values. The optimization solver and the formulation of the objective function are probable reasons. Additionally, Delil (1989) shows that the Morton number as a function of the temperature has a parabolic shape such that two solutions are indeed possible for one optimization problem. All other fluids (as listed in Table 4) consistently lead to worse matches with Z>0.1; even after repeated execution of the solver.

Case C: Condensing two-phase flow scaled by multiple π-numbers

For Case A and B, a parametric study on the temperature would have been sufficient to find the optimum. In Case C, neither a single parametric study nor a heuristic approach would quickly yield the optimal value of the objective function because it is a function of seven π-numbers and there are five variables to iterate on the objective value in addition to the fluid selection. As can be seen from the definition of the dimensionless numbers, the length and the heat flux only affect $\pi_4 = Eu_f = \Delta P/(\rho u^2)$ and $\pi_{14} = \dot{Q}/(\dot{m}h_{fg})$, hence, L_m and q'' can be calculated directly to achieve $\pi_{4,m}/\pi_{4,p} = \pi_{14,m}/\pi_{4,p} = 1$ without any penalty to the objective function. The objective value is then effectively a function of $\pi_2, \pi_3, \pi_7, \pi_8, \pi_9$ and the three iteration variables are T_m, D_m, u_m for any given fluid. Table 7 shows the optimization results for the six best matches to the prototype (top row). The best match is possible with the same fluid at the same temperature as the prototype with Z=0.043. This is explained by the two property ratios $\pi_7 = \rho_g/\rho_f$ and $\pi_8 = \mu_g/\mu_f$ which only depend on the temperature for a given fluid and significantly contribute to a decrease in the cost function when matched. The optimization result of the same fluid at the same temperature shows how the optimization algorithm finds a poor match for the gravity dependent π-number ($\pi_3 = Fr_f$) in favor of gravity independent π-numbers because all of them have the same weight in the objective function and two can be matched perfectly by the same fluid at the same saturation temperature. A similar Z value is obtained by R152a and Propane. R152a has the lower objective value but Propane has the smaller maximum deviation for any single π-number ratio. R134a and R143a achieve objective values of Z<0.15 as well.

Similar to Case B, there is some variability in the optimization result when comparing repetitive executions. Especially for the larger problem in Case C, the solver may also find local optimums instead of global optimums but the results differ only slightly.

Table 7: Results for Case C.

Order	Fluid	T [°C]	D [m]	u [m/s]	$\frac{\pi_{2,m}}{\pi_{2,p}}$	$\frac{\pi_{3,m}}{\pi_{3,p}}$	$\frac{\pi_{7,m}}{\pi_{7,p}}$	$\frac{\pi_{8,m}}{\pi_{8,p}}$	$\frac{\pi_{9,m}}{\pi_{9,p}}$	Z
Prototype	R600a	40.0	0.0050	0.010	1	1	1	1	1	0
1. Model	R600a	40.0	0.0036	0.0117	0.854	0.844	1	1	1	0.043
2. Model	R152a	32.0	0.0040	0.0090	1.003	0.617	1	1.098	0.9998	0.069
3. Model	Propane	8.7	0.0025	0.0151	0.783	1.322	1	1.067	1.0000	0.087
4. Model	R134a	23.8	0.0041	0.0073	0.885	0.496	1	0.931	1.0010	0.098
5. Model	R143a	-1.0	0.0054	0.0066	1.129	0.393	1	1.051	0.9999	0.113

DISCUSSION

Critique of Thermal Gravitational scaling

The benefits of thermal gravitational scaling are potentially overrated: The terrestrial (physical) models should simulate the prototypes as accurately as possible but the two-phase flow scaling has an inherent unquantified uncertainty and a perfect match of dimensionless numbers is probably not possible. For a system designer, these limitations may render the terrestrial model irrelevant and could explain why the work started by Crowley, Ungar, Delil and Hurlbert in the 1990s has faded afterwards. The open literature does not describe many case study examples where thermal gravitational scaling was essential in designing a thermal system for space. This would be important to achieve wide acceptance of thermal gravitational scaling as more than an academic exercise. Besides, a clear communication from space system designers about the interest in thermal gravitation scaling and applications of priority is needed.

Open questions about thermal gravitational scaling

Many questions are unanswered in the accessible literature. The following list presents several of them without claiming completeness:

- In addition to the Froude number, what other gravity dependent numbers should be added to the list of dimensionless numbers for two-phase flow?
- What is the gravity level that can be used in dimensionless numbers to approximate zero-gravity?
- What are real-world examples where thermal gravitational scaling is needed?
- Which group of π-numbers are essential for a given system?
- How much deviation between π-numbers is tolerable in the scaling process?
- What is the appropriate objective function once the set of essential π-numbers is found?
- Can thermal gravitational scaling leverage terrestrial inclination testing to predict reduced gravity system behavior?

CONCLUSIONS

Thermal gravitational scaling was an active research topic 20 to 30 years ago and it is unclear whether it faded because of the difficulty of finding a practical theory or disinterest within the space industry. The theories presented in the literature have not matured to the point that other engineers could easily apply them, because important information is missing, such as dimensionless numbers that have priority in the matching process and how much deviation is allowed if it is impossible to match all numbers. This paper presented a possible approach to thermal gravitational scaling by suggesting an objective function and different sets of dimensionless numbers for three case examples. Low objective values were simple to find for a small number of considered dimensionless numbers but the objective value increased when more dimensionless numbers were added to the objective function. Future work should include heat transfer dependent dimensionless numbers in the optimization and investigate the simultaneous scaling of multiple components in one system. In addition, feedback from the space industry is needed to understand potential applications and interest in thermal gravitational scaling.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support of Air Squared Inc.

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