SIMILITUDE MODELING IN RDC ACTIVITIES

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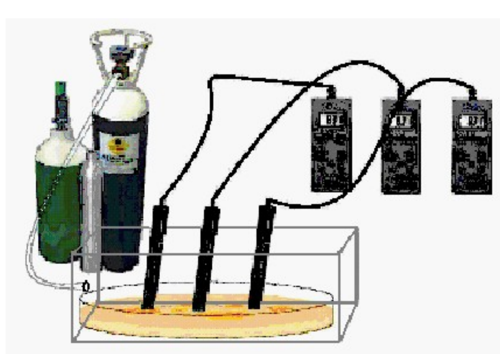
ABSTRACT

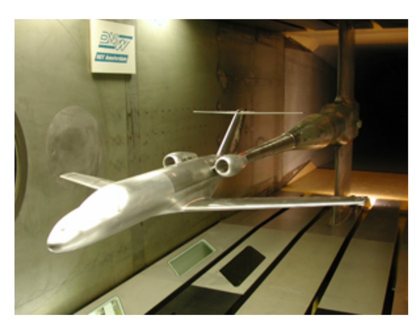
Research and development activities would involve the scaled modelling activities in order to investigate theory, facts, thesis or concepts. In commercialisation activities, scaling-up proses is necessary for the development of pilot plants or prototypes. The issue with scaled modelling is the similarity between the small scaled model and the full scaled prototype in all aspects of the system such as physical appearance, dimension and the system behaviour. Similarly, for scaling-up process, physical parameters and behaviour of a smaller model need to be developed into a bigger prototype with similar system. Either way, the modelling process must be able to produce a reliable representation of the system or process so that the objectives or functions of the system can be achieved. This paper discusses a modelling method which may be able to produce similar representation of any system or process either in scaled-model testing or scaling-up processes.

INTRODUCTION

Throughout the research, development and commercialisation (RDC) activities, more often than not there will be a process where the suggested idea or concept needs to be fully tested. For example, in chemical research, a new formulation study would be conducted in a laboratory with laboratory size apparatus. The study may produce the desired formulation under laboratory environment. However, if the same process would be transferred to a production plant, the same product may not be able to be produced similarly in all aspects as per laboratory product. For a large system or product, the experimental model used to investigate the characteristics and behavior of a system is often much smaller than the actual prototype due to constraints such as construction and operating cost. The example of such model testing can be found in motor vehicle, aviation and marine industry. The testing of new design would usually be conducted in wind tunnel facility for aerodynamic efficiency. To test a full model of an aircraft would require a huge facility that may incur exorbitant cost. Thus, smaller scale model with smaller wind tunnel is usually practiced in the industry. The similarity of the facility and the aircraft model to the actual situation is much more critical in this testing process. In nuclear power industry, apart from computational modeling, scaled down model of a plant is often become the necessary facility in testing the design as well as studying plant behavior in variety of situations. It is critical to have a representative system model that could predict the situation that might happen to the actual plant, so that the necessary remediation could be designed and implemented. Finally, bringing a process from laboratory to pilot plant would pose the scaling-up challenge to the engineers. Each process would require the appropriate and right scaling so that the desired product is similar to what have been proven in the laboratory production. Engineers always encountered with some greys parameters which either totally ignored, employing assumed parameters or getting the right technique to solve it. This paper presents the similitude modeling approach which may help to ensure the modeling process to produce models that behave in similar fashion as the prototype.



Laboratory experiment



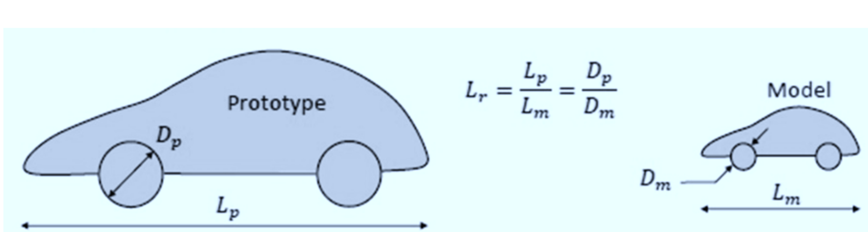
Wind tunnel modeling

Up-scaling process

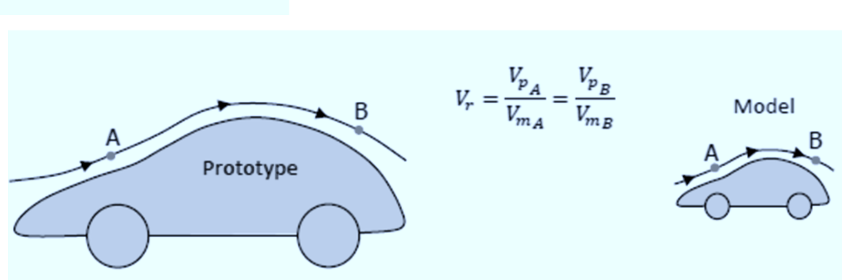
THEORY & METHODOLOGY

The theory of model which constitutes the relationship between the scaled size system (the model) and full size prototype are often studied using the concept of Dimensional Analysis. It is a theoretical tool that helps to understand the physics through the identification of governing equations from the analysis of dimensionality of the variables involved.

Similitude analysis is conducted to a model to ensure the results from the model can correctly be transferred to the prototype. The developed model shall meet the three similitude conditions, which are the geometric similarity, kinematic similarity and dynamic similarity. All of the three similitude requirements above may be accomplished through a method called Dimensional Analysis.



Schematics of geometric similarity



Schematics of kinematics similarity

Buckingham π theorem

The theorem states that for any dimensionless equation that involves k number of variables with r number of reference dimensions, may be reduced to a relationship having k – r number of independent π groups of dimensionless products. Therefore, all of the variables involved in the system shall be identified by understanding the physical law of the system. Then, the variables will be decomposed in term of basic dimensions such as M for mass or force, L for length, T for time and θ for temperature. This decomposition yielded the basic groups of pi terms representing the system.

The basic groups of π terms are then developed into a functional correlation that may represent the system through collection of experimental or simulation data which is then analysed further by regression analysis. The functional correlation which is supposed to represent the system is used to determine the parameters or dimension of the scaled model in relation to the actual system. The parameters of the scaled model are not necessarily having a linear correlation with the actual system.

APPLICATIONS

Consider a system that has the following variables that govern the system behavior: $h, H, \rho, \mu, C_p, k, g\beta dT$. The basic dimensions of the system are *mass, length, time* and *temperature*. According to Buckingham π theorem, the number of π group should be, n – r, which n = 7 variables and r = 4 basic dimensions. Thus, the number of π group is 7 – 4 = 3 p terms.

Let the functional equation $\pi 1 = f(\pi 2, \pi 3)$,

and the case is to consider its heat transfer behavior. Thus:

$h = f(H, \rho, \mu, C_p, k, g\beta dT)$

The form of basic dimension becomes:

$[M/T^3\theta] = f([L],[M/L^3],[M/LT],[L^2/T^2\theta],[ML/T^3\theta],[L/T^2])$

Employing Buckingham π theorem, all selected reference variables are eliminated using relevant mathematical principles, by inspection. In the end the following π groups are obtained:

$\pi 1 = hH/k$,

$\pi 2 = r\, C_p\, g\, bdT\, H^3 / k$,

$\pi 3 = C_p\, m / k$

The obtained π groups shall be developed further into a functional correlation which represents the system through numerical simulation or experimental study. The correlation is developed through regression analysis to come up with the proposed functional correlation and validated with the experimental data.

Resultant correlation for this case: $hH/k = 0.0989\, (r\, C_p\, g\, bdT\, H^3 / k)^{0.4583}$

Examples of modeling works which involved dimensional analysis: The investigation on impulse loading behavior from detonation of shallow-buried explosive (Grujicic and Glomski, 2013), the crushing behavior of onion varieties (Cakir et. al.,2001), cements compressive strength based on composition and setting time (Narvekar et. al.,2013), smoke filling time in compartment rooms (Nithirojpakdee,2013), theory of physiological similarity (Gunther & Morgado, 2003) and modeling of pollutants in river stream (Zelenakova et. al, 2013). All the modeling works went through the development of the dimensional analysis before came up with the dimensionless functional correlation/equations which may represent the system behavior in any scale that may be required.

CONCLUSION

The usage of testing models in research, development and commercialization activities as a proof of concept sometimes would encounter discrepancies between the model and actual prototype. This is due to the differences in environment, dimension and situation of both model and prototypes. This paper discussed the dimensional analysis approach which may produce a model which has similitude characteristics with the prototype. The analysis using Buckingham π method followed by regression analysis may produce a functional correlation which is in similitude condition between the scaled model and the actual full scale system. This approach may be applicable during plant process design and plant scaling-up works. It is also useful in predicting new nuclear reactor design and safety performance through the development of test rig models.