A Platform-Based Product Family Design Method Using Standardized Models with Physical Similarity Law and Its Application to Room Air Conditioners

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ABSTRACT

This paper proposes a "Platform-Based Design Method" concept using a standardized product reference architecture. Three examples cover a wide range from H/W key parts design with mechanical similarity law to standardized control S/W with reference algorithms architecture and an automatic UX design environment with machine learning. Firstly, we introduce a H/W design theory based on the similarity law of structural and fluid dynamics, using family design examples of various sizes outdoor units equipped with a new type hub less high-performance fan. A standardized heat exchanger circuit design optimization example with a robust distributor that improves the drift of liquid refrigerant is also shown. Secondly, we introduce parameter-adjustable S/W reference architecture P/F using universal 1D-lumped equation model for comfort airflow design. Third, in the scene of airflow control S/W development for indoor units, a front-loading design idea that combines thermal-fluid 2D-CFD with dimensionless numbers and reinforcement learning is proposed. The effectiveness of our auto-tuning method using Machine Learning with standardized CFD is proved through the RAC's User eXperience design.

1. INTRODUCTION

Toward the realization of a carbon-neutral society, it is expected that an energy-saving Air Conditioning System will be widely deployed all over the world using the product family design approach. From the manufacturer's point of view, an efficient local mass customization method by integrating standardized H/W devices (e.g., Heat exchanger, Refrigerant distributor, Axial fan, etc.) and reference S/W algorithm assets are needed to reduce the total product development cost and lead time to market. For example, the automobile industry has promoted a common platform (P/F) strategy to save development resources and costs through mass production effects. In academic papers, Fujita (2002) proposes an optimization method for product variety design and Sriram (2005) also proposes an idea related to knowledge support strategy and implementation example. We proposes a practical application example of platform-based product family design way using standardize reference formula for air conditioner product development.

2. PROPOSAL OF PLATFORM-BASED DEVELOPMENT METHOD

2.1 Structural definition of Air Conditioner product architecture

From customer's user experience view as the most important, we defined air-conditioning products architecture as the three-layer structure in Figure 1. For establishing competitive standard P/Fs in each layer and the maturation of system integration methods among the layers is a core competency of each company's competitiveness. Here, architecture means "the design concept behind specific individual technologies" or "the design philosophy that specifies the relationship between the complex system's subsystems". These qualities and quantities are tied to the unique corporate culture and unique assets have been accumulated and inherited through past product development in each organization.

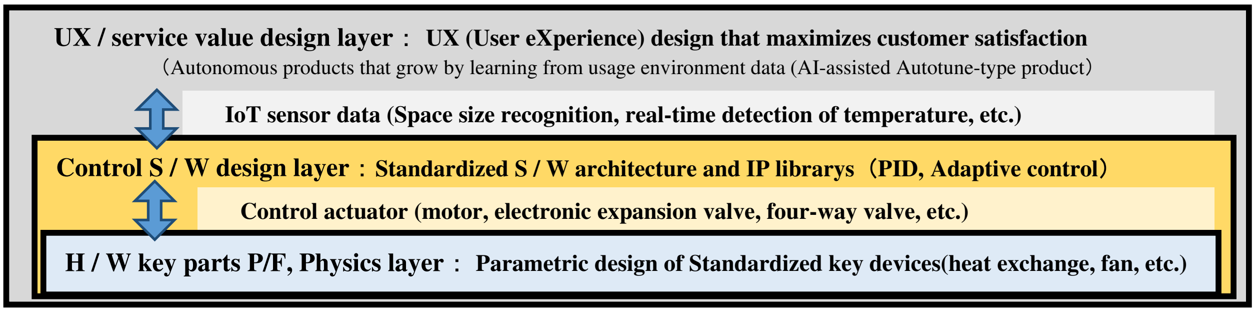


Fig.1 A proposed layered definition and platform-based integration relationship for air conditioning products

From the perspective of the modular configuration, Figure 2 shows the device module subsystems and p-h diagrams that make up the general vapor compression refrigeration cycle system often used in heat pump products. Typically, the main subsystems consist of an evaporator, condenser, compressor, expansion device and so on. During the product development project, the design of individual module devices can proceed in parallel with each mechanical designer. However, the operating balance point of the heat pump system is determined by the balancing of non-linear thermodynamic equilibrium interaction that occurs between each subsystem. Therefore, design variables parameter changes of each device and the evaluation of the system operating point are repeated many times toward the targeted design performance. For example, a lean system optimization method for similar hierarchical architecture-type household refrigerator products is proposed by Kobayashi et al (2021).

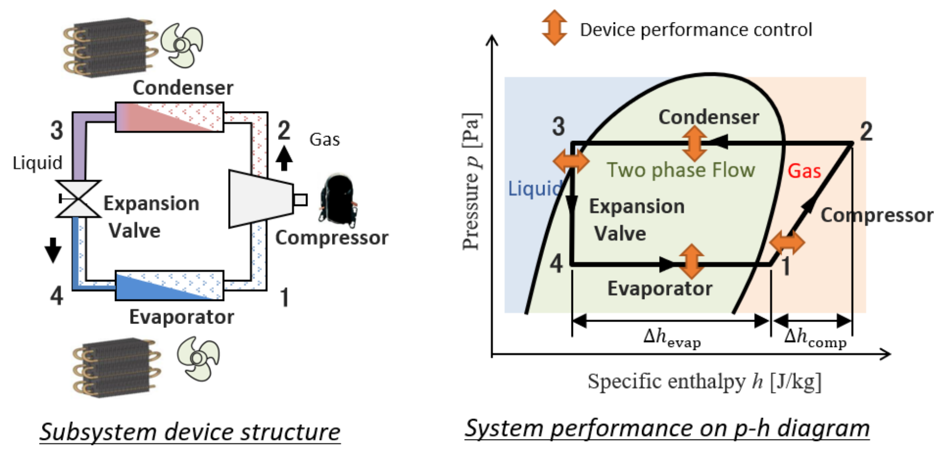


Fig.2 A schematic of the refrigeration cycle modules and system balance operation point on p-h diagram

2.2 Outline of proposed lean development framework

This paper extends a lean system design framework to Room Air conditioner. Figure 3 shows an image of deploying process from customer needs into product functions and then constructing a system from standardized modules. This process is divided into two phases: a phase to synthesize a tentative system configuration and a phase to analyze and verify its functions and performance specifically. In the system integration process, the design adjustment of each device is repeated step by step until the design value reaches the targeted whole system performance. To promote efficient system integration within a limited development time, the concrete key is also a practical lean process that effectively uses 1D and 3D analysis tools at each design phase and tacit decision making ability for synthesis. In other words, it is important to establish an organizational capabilities of "Right person in the right lean process using the right tools". In the next chapter, we will demonstrate it in detail using an example of a development application for a Room Air conditioner.

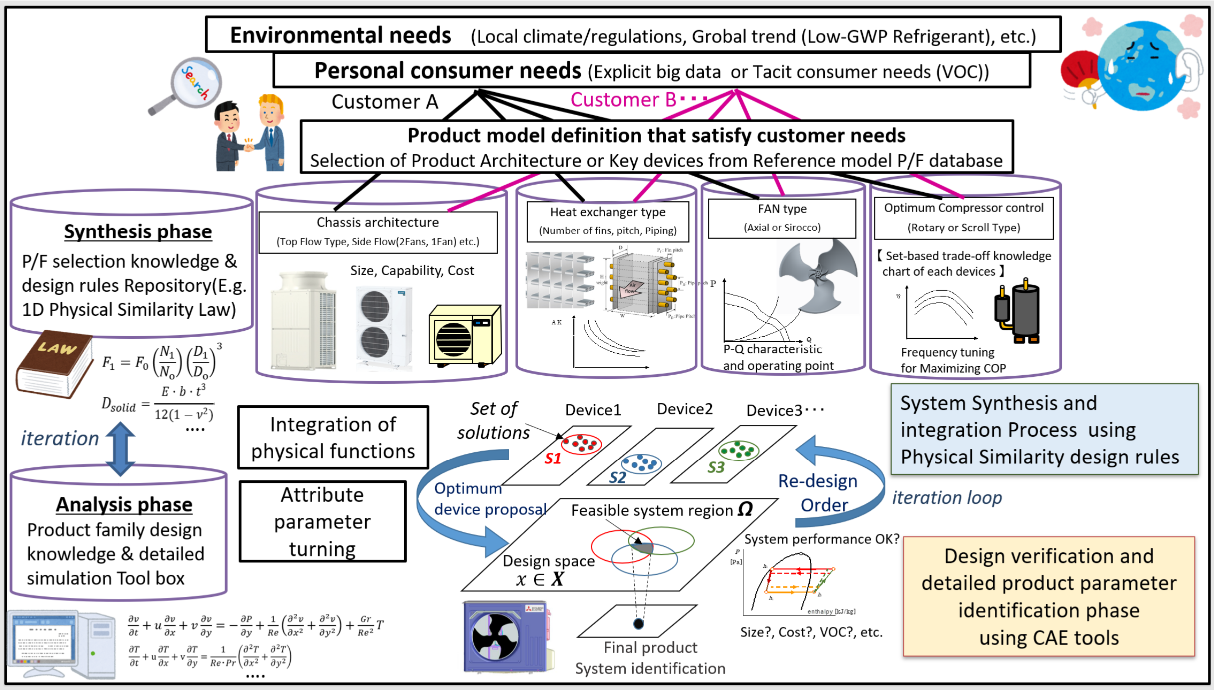


Fig.3 Proposed P / F based design framework which combines digital tool with tacit human knowledge for Air Conditioning product having hierarchical interaction between system and subsystem

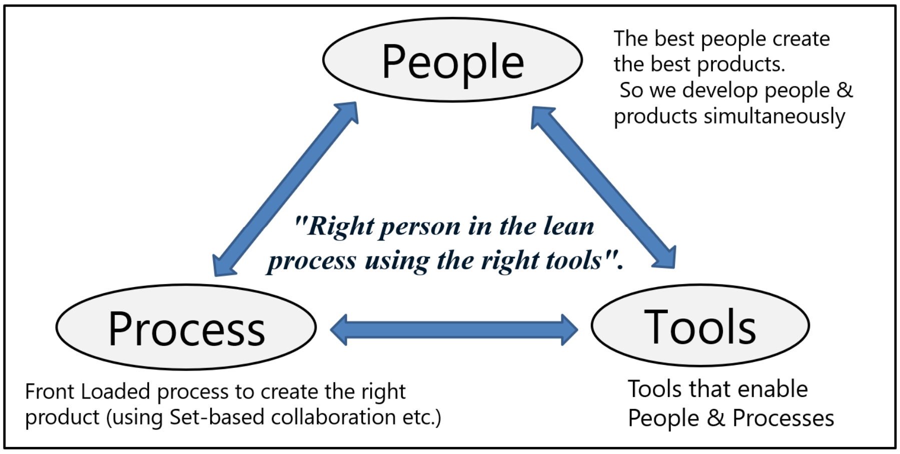


Fig.4 Socio-Technical Systems Model of Lean Product / Process Development
(Edited concerning Morgan and Liker (2006))

3. APPLICATION EXAMPLE OF PLATFORM-BASED DEVELOPMENT METHOD TO AIR-CONDITIONING PRODUCT DESIGN

3.1 Example of Platform-based H/W design using standardized mechanical similarity law

①Structural mechanical similarity design of axial fan for air conditioner outdoor unit

In the conventional axial fan shown in Figure 5, which was common in outdoor air conditioners, the fan blade is connected to the central cylindrical hub, which has high strength and rigidity, to prevent the destruction and suppress the blade vibration. When the fan rotates, the centrifugal force F_c is generated as shown in equation (1).

$$F_c = m_w \cdot r_w \cdot \omega^2 = m_w \cdot r_w (2\pi \cdot N)^2 \qquad (1)$$

Additionally, there are two key equations for wing deformation. Equation (2) can calculate the bending stiffness D_{solid}, which indicates the "resistance to bending" related to blade deformation. Equation (3) calculates the bending-torsion coefficient of the plate $E\Gamma$, which is related to the "torsion resistance." These equations show that the blade thickness direction and blade width b direction and the adjustment of the plate thickness t are essential parameters for the structural reinforcement. Follow these guidelines, a design strategy to increase rigidity by adding six reinforcing mini turbo blade type ribs to the leading and trailing edges of the main blades was adopted for the new fan.

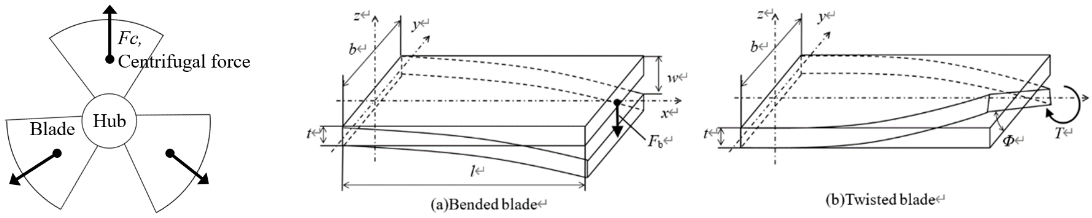
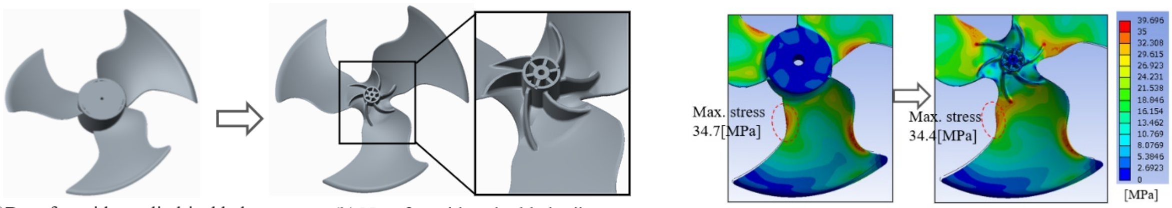


Fig. 5 Deformation image of blade when torsional force is applied

$$D_{solid} = \frac{E \cdot b \cdot t^3}{12(1 - \nu^2)} \qquad (2)$$

$$E \cdot \Gamma = E \frac{b^3 \cdot t^3}{144} \qquad (3)$$

After being inspired by the insights from above 1D-level structural principle equations, we have newly developed a high-efficiency fan with six mini turbo-blade ribs that relax the stress concentration on the blade edge (Fig.6(b)). The right side of Figure 6 is the stress result using 3D-FE Analysis at ϕ400 mm at 5000 rpm, assuming reverse rotation during a typhoon (Sachimoto et al., 2017). With this new shape fan, the amount of glass fiber reinforced plastic, which is difficult to recycle, could be reduced by 18% while maintaining the same strength. In addition, the aerodynamical static pressure efficiency η_s at the same flow rate could be improved by 7% compared to the base fan with the cylindrical hub (Hamada et al., 2021). When the diameter D or material of the new fan is changed, the mechanical similarity design can be done using these equations.



(a)Base fan with a cylindrical hub (b) New fan with turbo blade ribs (a)Base fan with a cylindrical hub (b) New fan with turbo blade ribs

Fig.6 Comparison of leading edge maximum stress between Base and New design FAN

②Fluid dynamic similarity design of axial fan for air conditioner outdoor unit

For example, the law of similarity of fans is introduced the handbook by Bleier (1997). It is described that for the same type of blower, the specific speed n_s is constant regardless of size, and the similarity relationship of equations (4)~(9) is established. Figure 7 shows the actual wind tunnel test results with a similarly enlarged prototype fan with three different fan diameters D(ϕ360, ϕ400, ϕ440mm). From these our single fan experimental results, it can be confirmed that the similarity law concerning the relationship between "static pressure efficiency η_s and pressure drop coefficient ξ" and "dimensionless fan Ψ_s-φ characteristic" is actually established. Using this single fan characteristics, it can be adjusted by diameter D and rotation speed N according to the required airflow rate F. Since the fan aerodynamic noise dB can be also estimated by equation (9), the fan diameter D is enlarged in accordance with the enlargement of the box size in the large capacity outdoor unit, and the rotation speed N is reduced to lower the acoustic noise. As shown above, once a highly competitive key parts P/F and design knowledge database can be established, product deployment is easy by using these physical similarity rules. Figure 8 shows an actual example of similar deployment of new fans with different diameters to various capacity outdoor family unit.

$$F_1 = F_0 \left(\frac{N_1}{N_0}\right)\left(\frac{D_1}{D_0}\right)^3 \tag{4}$$

$$\Psi_s = \frac{2 \cdot \Delta P_s}{\rho (D \cdot \pi \cdot N)^2} \tag{5}$$

$$\varphi = \frac{4 \cdot F}{\pi \cdot D^2 \cdot N(1 - \nu_{hub}{}^2)} \tag{6}$$

$$\bar{L} = \frac{L}{\rho \cdot N^3 \cdot D^5} \tag{7}$$

$$\eta_s = \frac{F \cdot \Delta P_s}{L} \tag{8}$$

$$dB_1 - dB_0 = 10\, log_{10}\left(\frac{D_1}{D_o}\right)^5 + 10\, log_{10}\left(\frac{N_1}{N_o}\right)^5 \tag{9}$$

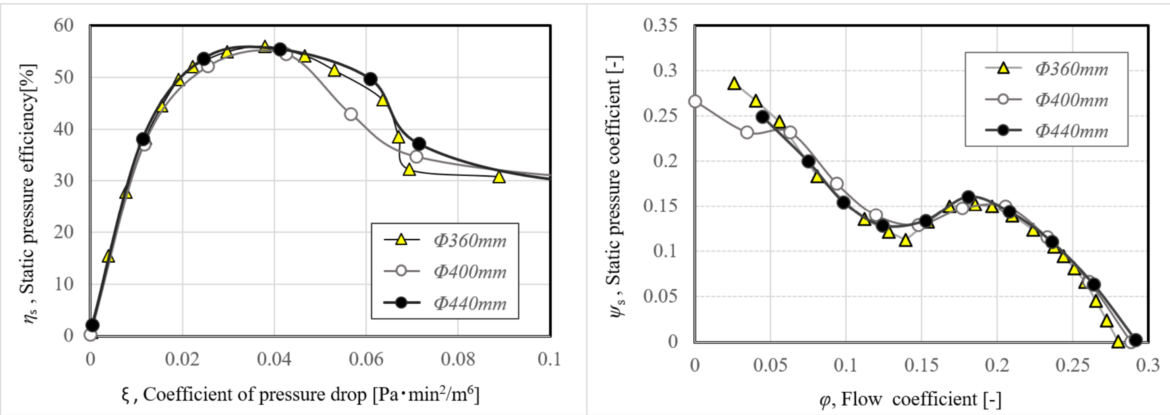


Fig.7 measured single fan's dimensionless fluid performance with three different D(Φ360, 400, 440mm) prototypes

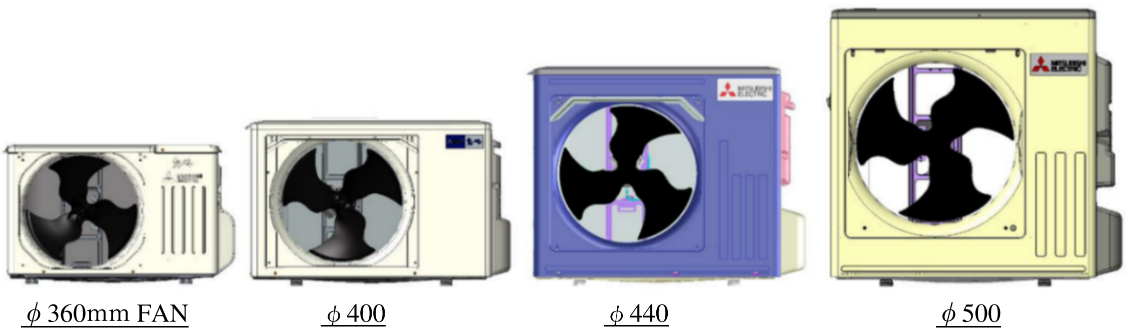
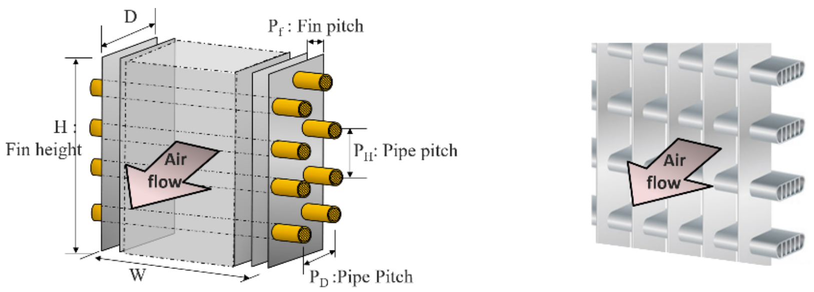


Fig.8 Product family deployment example of new fans based on similarity rules for various size outdoor units

③Similarity design in heat transfer engineering for heat exchanger performance
In the performance design of the outdoor unit's heat exchanger, the designer first selects a standardized basic core structure such as circular fin tubes or flat tubes, etc as shown in Figure 9. For example, the front surface area of the heat exchanger, A_{front}, is roughly calculated based on the target capacity, Q. The number of rows of fins and the pitch size of fins is calculated by considering the heat transfer similarity laws in equations (10) to (12). Where K_x is the local heat transfer coefficient between refrigerant and air. In particular, if equation (13) is kept constant by adjusting the width W and total airflow rate F to match the heat flux q between fins one pitch P_f and the air velocity v_f of between fins, the heat exchange-to-air temperature difference ΔT_{eva}, which significantly affects the system COP, will also be kept constant. As a result, thermodynamic similarity can be controlled as a common energy-saving design concept even among family products with different capacities.



(i)Fin and circular tube (ii)Mini-channel flat tube

Fig.9 An example of a standardized heat exchanger core for parametric design

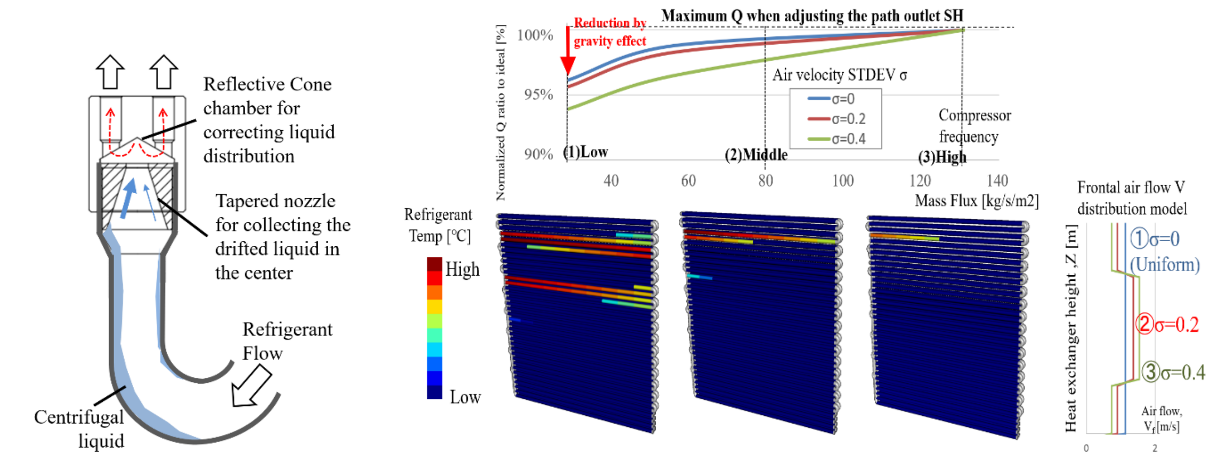
$$Q_{\mathrm{HEX}} = G \cdot \Delta h = \int K_{\mathrm{x}}(T_{\mathrm{a,x}} - T_{\mathrm{ref,x}}) \mathrm{d}A_{\mathrm{fin}} \propto A_{\mathrm{front}} \tag{10}$$

$$\Delta T_{\mathrm{HEX}} = T_{\mathrm{a,in}} - T_{\mathrm{ref}} = \frac{Q_{\mathrm{HEX}}}{A_{\mathrm{front}} \cdot v_{\mathrm{f}} \cdot \rho \cdot C_{\mathrm{p}} \{1 - \exp(-NTU)\}} \tag{11}$$

$$\boldsymbol{NTU}(Number\ of\ Transfer\ Units) = \frac{\mathrm{K} \cdot \mathrm{A}}{F \cdot \rho \cdot C_{\mathrm{p}}} \tag{12}$$

$$\frac{Q_{\mathrm{HEX}}}{A_{\mathrm{front}} \cdot v_{\mathrm{f}}} = Constant \tag{13}$$

④Thermodynamic similarity design for heat exchanger performance
The similarity design of the two-phase flow pattern in the pipe is also considered by using Baker diagrams. However, when the refrigerant mass flow rate G is reduced at low capacity, the flow regime in the tube transitions from annular to stratified wavy flow field, and the liquid flow becomes biased due to the centrifugal effect at the tube bend. In addition, due to the gravity effect, the liquid refrigerant supply to the upper heat exchanger path is insufficient. The outlet superheat, which may cause the similarity of the heat exchange temperature distribution to be broken. Therefore, a tapered nozzle and a reflective chamber structure are installed in the distributor to correct the uneven liquid refrigerant flow (Fig.10(a)). If the shortage of liquid in the upper path due to the gravity effect is predicted from the analysis with "Coil Designer" as shown in Figure 10(b), that problem will also be taken care of in advance and adjusted for each branch length (Hattori et al.,2021). Here the Coil Designer was developed by Jiang and Aute et al.(2006). So, the circuit of the final heat exchanger can be robustly mass-customized for a wide range of capacities in advance by using this standardized design method.



(a)A distributor design to collect drifted liquids (b)Sensitivity analysis of fluid deviation on HEX performance

Fig.10 An example of recovering the performance reduction of HEX due to gravity effect on liquid refrigerant

3.2 Examples of Platform-Based S/W Design using standardized reference control architecture

This chapter introduces S/W parameter-adjustable control P/F for comfort airflow design using universal 1D lumped nodal capacitance model. In air conditioners, the flap angle θ for wind direction control and the rotational speed of actuators such as fans and compressors are controlled by S/W to adjust the temperature, humidity, airflow comfort, etc. in the target area. So, it is also important to create a standard P/F for not only H/W key parts but also S/W algorithms for actuator control. If the system can be assumed to be a lumped nodal system, it can be universally treated as a similar phenomenon based on the time constant τ (=*R***C*) issue. For example, in the SISO (Single Input and Single Output) control P/F, the Look-up Table (LUT) method and PID(Proportional-Integral-Differential) controller are effective, however the control table and PID gain constants (K_p, K_I, K_D) must be determined in advance. Model Predictive Control (MPC) a is also promising method, however when the room temperature is modeled as a 1D nodal network plant in a fully mixed system with the average $\overline{T}_i$ as like equation (14), accuracy problems due to the lack of spatial resolution of temperature distribution and each heat capacity C in a room (Fig. 11) still remained.

$$\Sigma C^{*}\frac{d\overline{T}_i(\mathrm{t})}{\mathrm{dt}} = U\cdot A\left(\overline{T}_o - \overline{T}_i(t)\right) + Q(t) \tag{14}$$

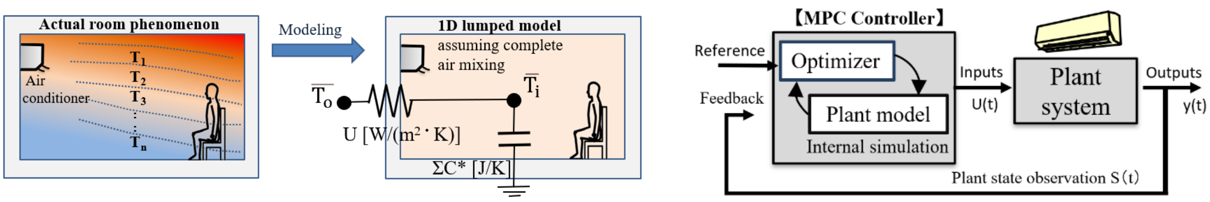
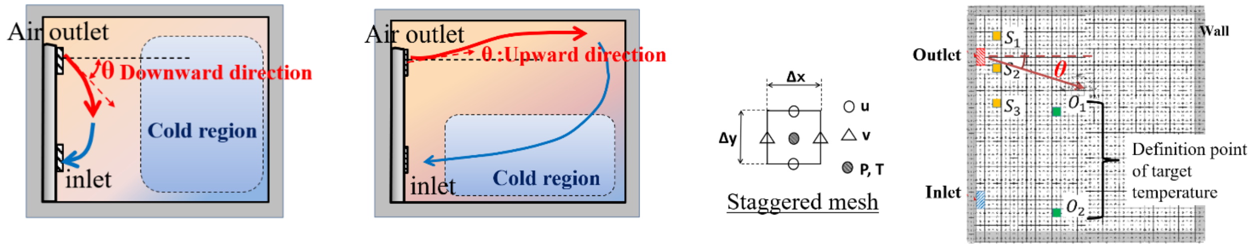


Fig.11 Difference between actual room phenomenon and Model Predictive Control (MPC) with 1D lumped model

3.3 Examples of Platform-Based UX Design using normalized CFD tool P/F

This chapter introduces a PoC on intelligent air flow control adjustment method using reinforcement learning in indoor unit. In the theme of control the temperature/humidity/velocity field of a indoor room, air conditioners are required to adapt to various environments, such as the dimensional aspect ratio of the room and the U-value as the wall thermal transmittance (Fig. 12(a) and (b)). Such spatial convection problems have strong nonlinearities and cannot be treated as simple 1D-level nodal capacitance model, so we attempted to make a standardized design platform using normalized 2D CFD with dimensionless numbers such as Re, Gr and Pr. If this design control P / F tool can be made, it is also expected to shorten the lead time using CFD based control design with any combination of room size and wall insulation coefficient U value. In this proof of concept, a heating mode of a floor-standing RAC was assumed and the flow velocity v, temperature T, and air flowing direction θ were given to the outlet at the top of the left wall as boundary parameter. At the same time, the return inlet was set at the bottom left as like in Figure 12(c).



(a)Fluid short circuit (b)Temperature stratification by buoyancy (c) Dimensionless staggered mesh model

Fig.12 Cases of dissimilar phenomena in indoor space and dimensionless numerical analysis mesh model

The 2D CFD mesh shown in Figure 12(c) made standardized and has a grid number of 784 (n_x=28, n_y=28), which can be used for various room sizes by adjusting the values of the unit mesh length Δx(=X/ n_x) and Δy(=Y/ n_y) for each room geometry. In this CFD, 2D Navier-Stokes equations (15) and (16), which are made dimensionless by Re, Gr, Pr number and continuity equation (17) and energy equation (18) are coupled using the Marked and Cell method. We also attempted to automate this control design environment platform by combining CFD and reinforcement learning (Ikeda et al., 2019). As a reinforcement learning strategy, we aimed to minimize the difference between the upper and lower room air temperature and the reward value was evaluated using equation (19) with the temperature ratio of the observation points O_1 and O_2. Here, in Q-learning, the randomness adjustment parameter ε-greedy constant was set to 0.5, learning coefficient α in state equation (20) was set to 0.1, and discount rate considering long-term effects γ was set to 0.5. Figure 13 shows the automated learning process flow with changing the reward value r_t and converging image toward the target design. After reinforcement learning based on equation (20), the flowing direction flap angle θ in the Q-table converged to about 10° after five epochs, and the PoC for automation of control adjustment was achieved.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{15}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial P}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{Gr}{Re^2}T \tag{16}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{17}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{Pr \cdot Re}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + S \tag{18}$$

$$\boldsymbol{r_t = \frac{1}{\sqrt{2}}\left(\exp\left(-\frac{(ratio - 1.0)^2}{2}\right)\right)} \tag{19}$$

$$Q(s_t, a_t) \leftarrow (1-\alpha)\cdot Q(s_t, a_t) + \alpha\left(r_{t+1} + \gamma max_{a_{t+1}}\cdot Q(s_{t+1}, a_{t+1})\right) \quad (20)$$

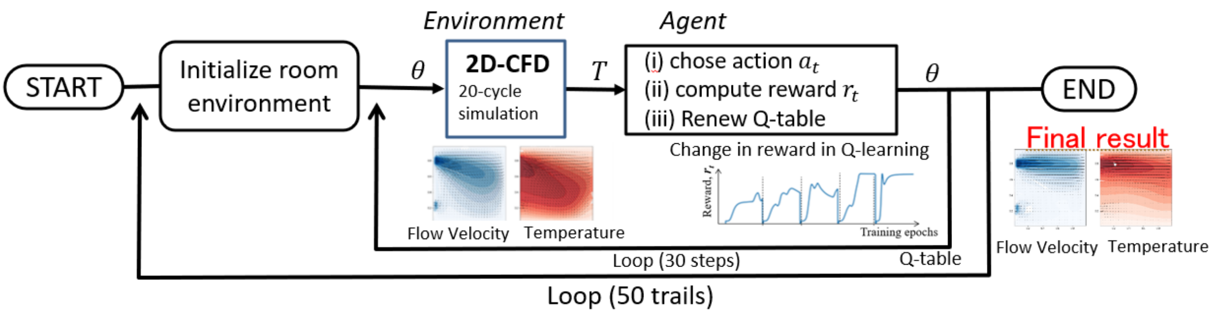


Fig.13 Proposed Machine Learning scheme using 2D-CFD for identifying optimal control parameters

4. CONCLUSIONS

We proposed a "Platform-based product family design method using reference physical similarity law" for the air conditioning products and presented its application example cases. Three examples cover a wide range from H/W key parts design with mechanical similarity law to standardized control S/W using reference architecture and an automatic UX design P/F environment with machine learning. In other words, our reference based framework can be said to have general universality regardless of the target field. Our P/F-based development package is also effective in tacit knowledge transfer from the mother factory to global sites and accelerating design localization. These explicit design rule reference model D/B are also applicable in promoting design automation system in the near future. If we use a diagram with a Model-Based Development-like vee representation, this process can also be expressed like Figure 14. In conclusion, our Model-based lean way using a product platform effectively reduces development time for hierarchical architecture type vapor compression air conditioning cycle systems. By refining and expanding this method widely to our energy-saving product family, we will make a sustained contribution to a zero-carbon society.

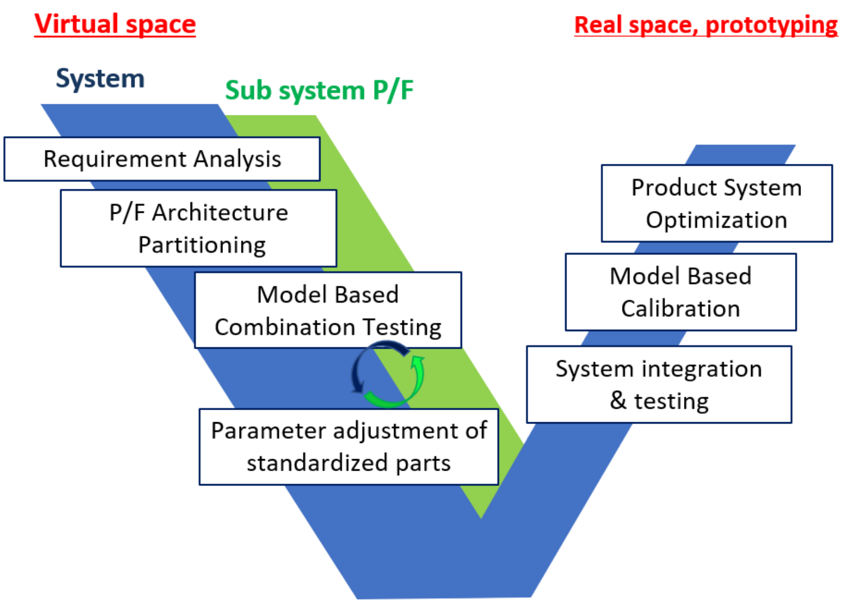


Fig.14 Parallel Vee representation from Model-Based P/F Development perspective

NOMENCLATURE

D	fan diameter	(m)
D_{solid}	bending stiffness	(Pa・m^4)
E	elastic modulus	(Pa)
F_c	centrifugal force	(N)
Gr	Grashof number	(-)
L	input shaft power	(W)
$\bar{L}$	dimensionless power coefficient	(-)
m_w	mass of one blade	(kg)
n_s	specific speed	(-)
N	rotation speed	(rps)
Pr	Prandtl number	(-)
Q	quantity of heat	(W)
Re	Reynolds number	(-)
U	wall thermal transmittance	(W/m^{2}K)
Γ	warping constant	(m^6)
ν	Poisson's ratio	(-)
ν_{hub}	hub ratio	(-)
ξ	pressure drop coefficient	(Pa・min^2/ m^6)
ω	angular velocity	(rad/s)

Subscript

HEX	Heat Exchanger
ref	refrigerant
x	local

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