DAIKIN Project

Title

Design Optimization and Modeling of Phenomena in Air Conditioner

Industrial Partner DAIKIN Industries, Ltd.

Daikin is the world's only comprehensive air conditioning manufacturer that manages everything in-house, from refrigerant development and equipment production to sales and after-sales service, and it holds the No. 1 position in sales in the air conditioning market. Under the action plan 'FUSION25' aimed at achieving ‘carbon neutral’, the company is working on creating new products, services, and business models, as well as fundamentally innovating business processes. Additionally, it is promoting digitalization as a theme for strengthening its management foundation.

Background

In promoting digitalization, mathematical simulation is a key technology to DAIKIN. By using mathematical simulations, the need for prototypes for verification and comparison is eliminated. This enables more testing in a shorter time than what it takes to build prototypes, thereby enhancing development efficiency. Mathematical simulation allows us to visualize phenomena that are difficult to observe. By visualizing information that is hard to capture with sensors, such as the airflow or refrigerant’s flow, we can intuitively understand what is happening. This not only helps in explaining the underlying principles of the phenomena but also serves as a valuable tool for communicating with both internal and external audiences. It is particularly persuasive when explaining airflow to customers who are not HVAC specialists. Through mathematical simulations, it is possible to provide optimal proposals and designs by clarifying mechanism and balancing numerous requirements at a high level. It becomes possible to role-play countless scenarios in planning and design, and to verify them. This allows for the development of concrete strategies with high feasibility in a short amount of time.

Industry Mentors

Satoru TAKANEZAWA
Technology Innovation Center
DAIKIN Industries, Ltd.

Project overview & Expectations

Two fundamental problems in the use of mathematical simulation for air conditioning design arise:

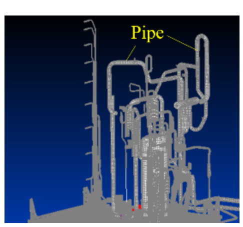
✓ [Required]: Routing of Piping Curve to Compromise Stress and Noise in Outer Unit

✓ [Optional]: Identification of Physical Properties taking into account of Micro-Structure of Refrigerant Flow in Heat Exchanger

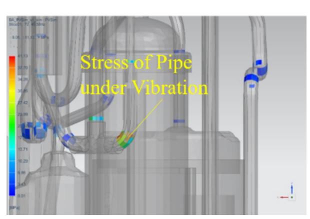
Students are expected to work on the second project if the first project is completed timely, or if there are any unworkable issues blocking progress on the first project.

◇ **<u>[High Priority] Routing of Piping Curve to Compromise Stress and Noise in Outer Unit</u>**

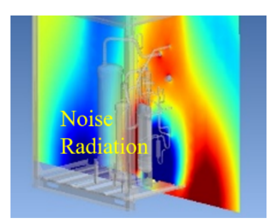
In the process of air conditioner (AC) development, one of the most time consuming problems is to compromise between the stress of pipe under vibration and noise radiation from the outer unit. To reduce the lead-time of development, increasing the speed of the pipe design process is important.



Pic1. Piping



Pic2. Stress of Pipe



Pic3. Noise Radiation

The key structural factor controlling these phenomena is the routing of piping curve. This means that the mechanical characteristics of the outer unit depend on the routing of piping curve. Stress occurs according to the curvature of the pipe under vibration, which is due to the dynamic properties of the pipe. The dynamic properties are controlled by the boundary condition, stiffness, and density distribution of the pipe. Noise radiation occurs according to the vibration of the casing on the outer unit, which is excited by the force transmission from the pipe. The force transmissibility is due to the mechanical characteristics of the pipe. Therefore, we can understand that the routing of piping curve is the key factor to both the stress of the pipe under vibration and noise radiation from the outer unit, so a method to optimize the routing of piping curve is required to compromise between the stress and noise in the outer unit.

<u>Goal</u>

Propose a method to optimize the routing of piping curve to compromise between the stress and noise in the outer unit of the AC.

<u>Expected Approach</u>

The critical point of piping stress under vibration is derived by the Euler-Lagrange equation through the energy of vibration like below. *y* is a parameter along pipe. *v* is the displacement. *f* and *g* are given functions. ρ is the density. ı is the curvature. *M* is the Von Mises stress.

$$
\begin{aligned}
&v(y,0) = 0 && y \in \overline{M} \\
&v(y,t) = f(y,t) && (y,t) \in D_1 \times \mathbb{R}, \\
&[V]n = 0 && (y,t) \in D_2 \times \mathbb{R}, \\
&\rho \frac{\partial^2 v}{\partial t^2} = \nabla \cdot {}^T[V] && (y,t) \in M \times \mathbb{R}, \\
&\iota(y) = g(y) && y \in D_1, \\
&[G]n = 0 && (y,t) \in D_2 \times \mathbb{R}, \\
&[G]\nabla(\mathcal{M}[v,\iota])^2 = 0 && (y,t) \in M \times \mathbb{R}.
\end{aligned}
$$

$$
\begin{aligned}
[V] &:= \mu\left[\frac{\partial v}{\partial y}\right] + \mu\left[\frac{\partial \iota}{\partial y}\right]^T\left[\frac{\partial v}{\partial y}\right]\left[\frac{\partial \iota}{\partial y}\right] + \lambda \mathrm{tr}\left(\left[\frac{\partial v}{\partial y}\right]^T\left[\frac{\partial \iota}{\partial y}\right]\right)\left[\frac{\partial \iota}{\partial y}\right], \\
[G] &:= \left(3\left[\frac{\partial \iota}{\partial y}\right]^T\left[\frac{\partial v}{\partial y}\right] + 3\left[\frac{\partial v}{\partial y}\right]^T\left[\frac{\partial \iota}{\partial y}\right] - 2\mathrm{tr}\left(\left[\frac{\partial v}{\partial y}\right]^T\left[\frac{\partial \iota}{\partial y}\right]\right)[I]\right)\left[\frac{\partial v}{\partial y}\right].
\end{aligned}
$$

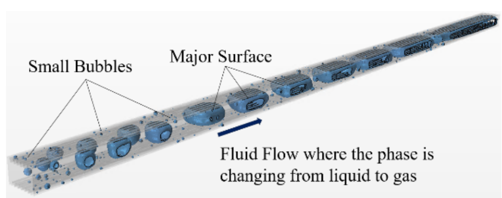
The update of the Euler-Lagrange equation is expected, taking into account force transmission through the pipe. If possible, numerical analysis to solve these equations is expected. Additional mathematical analysis of these equation is welcome, such as existence of solution, the number of critical points, stability, etc.

Mathematical requirement (Better to know, Have not to know)

Calculus of variation, Hamiltonian mechanics, Mechanics of deformable solids

- ◇ **Identification of Physical Properties taking into account of Micro-Structure of Refrigerant Flow in Heat Exchanger**

To maximize energy efficiency of the AC, a key design is the control of refrigerant flow. Air Conditioners are operated by the principle of the refrigerant cycle, which is a kind of thermo-mechanical cycle. The refrigerant is a material whose phase changes easily between liquid and gas under operation condition of AC. So that, the refrigerant flows with a surface between liquid and gas under the operation of the refrigerant cycle. The shape of surface is very complicated and that changes transiently due to flow and phase changes.



Pic4. Fluid Flow with Phase change

We have been trying to solve the motion of these surfaces mathematically. However, the tracking of every surface motion with very small bubbles is rather unrealistic to analyze. Therefore, we would solve only the major motion of the surface and hopefully ignore small structures of surface motion. We would solve refrigerant flow as a homogenized fluid with physical properties, while taking into account small structures of the surface.

With this approach, we can solve the refrigerant flow using standard numerical schemes for the Navier-Stokes Equation.

Goal

Express the physical constant of the Navier-Stokes Equation taking into account the microstructure of the refrigerant, especially regarding the liquid under the dispersion state of microbubbles. If possible, express the physical constant of the wave equation in the same way.

Expected Approach

Homogenization, which is a mathematically well defined method is expected. Some references are refs. [1] and [2].

Mathematical requirement (Better to know, Have not to know)

Functional analysis, Partial differential equation (Navie-Stokes equation)

References

[1] Allaire, G., Homogenization and Two-Scale Convergence.

[2] Bensoussan, A., Lions, J.-L., Papanicolaou, G., Asymptotic Analysis for Periodic Structures.