Intro to Forced Convection

Forced Convection in External Flows – Lesson 1

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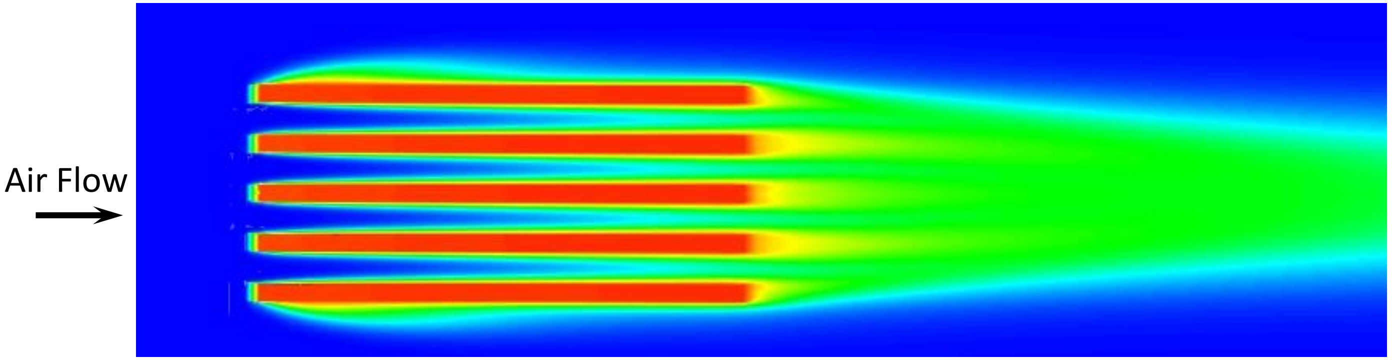
Intro to Forced Convection

- In general, convection is the process of thermal energy transfer that occurs due to fluid motion.
  - For example, if air is blown across a heated plate, the downstream air is hotter – thermal energy has been transferred into the fluid and carried by it to another location.
  - How does the heat enter the fluid? How much thermal energy can be transferred? How does the nature of the fluid flow affect the rate of heat transfer? These questions are addressed by the science of convective heat transfer.
- Convection is classified into forced and natural (free) convection based on the mechanism responsible for creating the fluid flow:
  - In forced convection, the flow is generated by external means, e. g., wind or a fan, or by the object's motion through a fluid.
  - In natural convection, the heat transfer itself is the primary mechanism behind the fluid motion, which is generated by the buoyancy force due to temperature gradients.
- In this course, we will focus our discussion on forced convection.

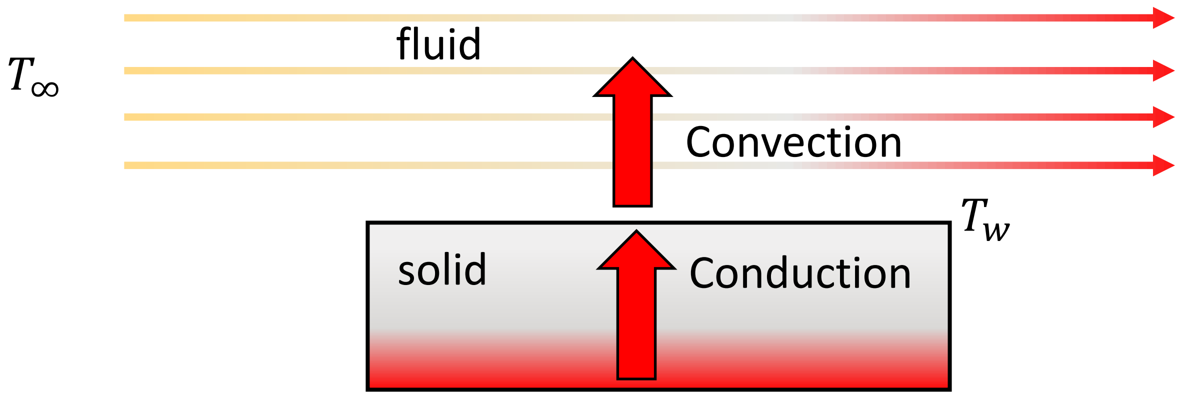


Temperature distribution in the air as it flows over a hot heat sink to extract heat through the process of forced convection

Newton's Law of Cooling/Heating Revisited

- Consider Newton's Law of cooling/heating at a point on our heated plate. Let the local convection heat flux be represented using the heat transfer coefficient h, the incoming fluid temperature T_∞ and wall temperature T_w.
- At the wall, there is no motion due to the no-slip condition and the conduction heat flux in the fluid is described by Fourier's Law.
- These two fluxes must be equal at the wall (neglecting radiation), thus:

$$q''_W = h(T_w - T_\infty) = -k_f \frac{\partial T}{\partial y}\Big|_w$$



Local and Average Heat Transfer Coefficients

- In general, heat transfer is a function of space, so the heat transfer coefficient will vary (sometimes substantially) over a surface.
- Accordingly, a local heat transfer coefficient can be defined based on the local heat flux q''_w and wall temperature, T_w, as shown on the previous slide.
- For engineering purposes, an average heat transfer coefficient value for a surface is often needed in order to estimate the heat transfer. Therefore, the local value can be area-averaged (denoted by the overbar) as follows:

$$\bar{h} = \iint_A \frac{q''_w}{(T_w - T_\infty)} dA$$

Then, the total heat transfer rate is:

$$q = \bar{h} A (T_w - T_\infty)$$

- Note that the sign of the local heat flux q''_w should be consistent with the local temperature difference $T_w - T_\infty$ such that h is always a positive number.
- The essence of the problem of convection is determining the local and averaged heat transfer coefficients, which can subsequently be used to calculate the local flux or the total heat transfer rate.
- It is common to abbreviate the terms “heat transfer coefficient” as HTC, and we will be using this abbreviation throughout this course.

The Nusselt Number

- Let us now non-dimensionalize the wall heat flux balance equation using L (reference length) and T_∞ (reference temperature). All the parameters (T_W, T_∞, h, k_f) are assumed to be constant. Denoting non-dimensional quantities with *, the heat flux balance can be rewritten as:

$$\frac{hL}{k_f} = -\frac{T_\infty}{(T_W - T_\infty)} \frac{\partial T^*}{\partial y^*}\bigg|_W \equiv Nu$$

- The term on the left is known as the Nusselt number (Nu). We will use the Nusselt number as a non-dimensional measure of convective heat transfer relative to heat transfer that would occur by conduction into the fluid.
- As defined, the Nusselt number is local if the heat transfer coefficient is local. If we employ the average heat transfer coefficient, we obtain the average Nusselt number:

$$\overline{Nu} = \frac{\bar{h}L}{k_f}$$

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The Reynolds and Prandtl Numbers

- The Nusselt number is found to correlate with two dimensionless parameters associated with the momentum and energy equations, namely:

  - The Reynolds Number $$Re = \frac{\rho V L}{\mu}$$

  - The Prandtl Number $$Pr = \frac{C_p \mu}{k} = \frac{\nu}{\alpha}$$

- The Reynolds number represents the ratio of inertial forces (represented by $\rho V L$) in a flowing fluid to the viscous forces (represented by μ).
- The Prandtl number represents the ratio of viscous diffusion of momentum (represented by $\nu = \mu/\rho$) to thermal diffusion in the fluid (represented by $\alpha = k/\rho C_p$).

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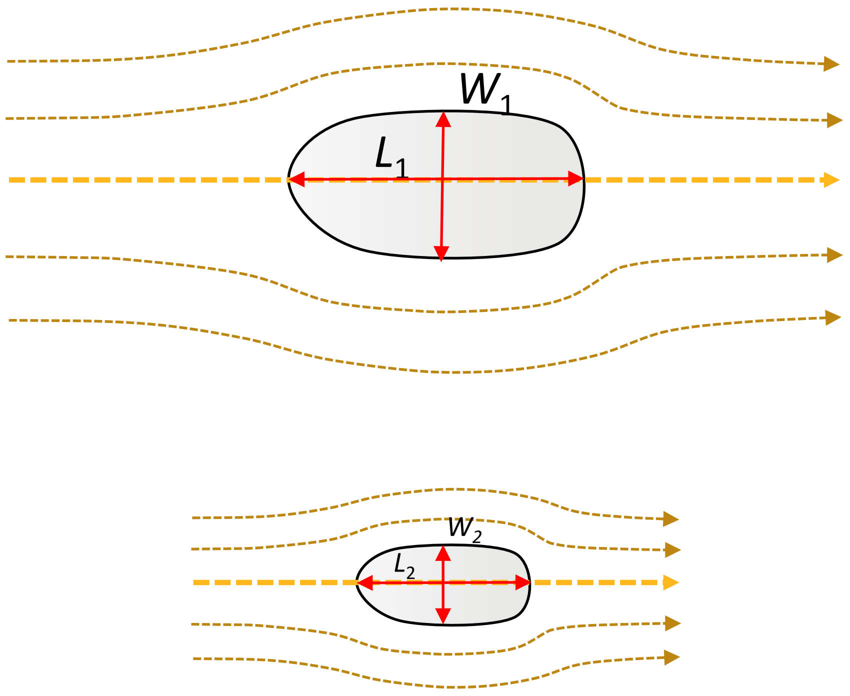
The Reynolds and Prandtl Numbers (cont.)

- One of the central themes in convection heat transfer is determining the heat transfer coefficient for specific flow configurations, e. g., flow over a heated cylinder, flow in a pipe, etc.
- This can be accomplished in two ways:
  - Run a series of experiments in which key geometric and thermal parameters are varied and measured carefully. For example, we can measure the heat flux from a cylinder of diameter D which is maintained at a specific surface temperature and exposed to a fluid flow at a given freestream temperature and velocity.
  - Run simulations wherein the governing equations are solved using CFD techniques for specific geometries and flow/thermal boundary conditions. This is akin to doing an "experiment," except now we are simulating the flow field numerically.
- It is impractical to perform experiments or run simulations for every conceivable geometry and flow/thermal condition. Is there a way to generalize the physics? The answer is yes! We can use Similarity Methods and Dimensionless Groups to develop correlations for common geometries and flow configurations.

Geometric and Dynamic Similarity

- Consider a flow over two objects, where the smaller object represents a physical model of the larger.
- Geometric similarity refers to the requirement that the ratio of all corresponding lengths of the two objects (L1/L2, W1/W2) are the same.
  - Another way of saying this is that the two objects are perfectly scaled geometrically.
- Dynamic similarity is the requirement that if the two objects are geometrically similar, then they also have similar flow patterns, i.e., the velocities and velocity gradients, fluid forces and streamlines all scale with the geometry.
- For heat transfer problems, we will also require that the temperatures, temperature gradients and heat fluxes scale with the geometry.



Geometric and Dynamic Similarity (cont.)

- As in fluid dynamics, formal methods can be used to determine the relevant dimensionless groups for convection heat transfer.
  - The Nusselt number is a non-dimensional representation of heat transfer.
  - The Prandtl number represents the relative sizes of the thermal and velocity gradients.
  - The Reynolds Number is a non-dimensional representation of the fluid dynamics (ratio of inertial to viscous forces).
- The requirement for similarity then is that the dimensionless groups (both flow and thermal) are the same for a geometrically similar system.
- For the case of forced convection, two geometrically similar systems are dynamically similar if their Nusselt, Reynolds and Prandtl Numbers are the same.
  - Therefore, if an experiment is run with a model geometry at given Reynolds and Prandtl numbers to determine a Nusselt number, then the Nusselt number results can be applied to a scaled-up version of the model provided the Reynolds and Prandtl numbers are the same.

Heat Transfer Correlations

- Let's consider a convection scenario, such as flow over a heated object of size L, with the objective to experimentally determine how the heat transfer varies with the geometry size and flow conditions.
- From the similarity discussion, a test matrix would be set up where the Reynolds and Prandtl numbers are systematically varied and the Nusselt number is calculated from the data obtained from the tests.
- Could a relationship between the Nusselt number and Reynolds and Prandtl numbers be found? That is:

$$Nu = F(Re, Pr)$$

- It turns out, the results for a given fluid (i.e., fixed Pr) fall close to a straight line on a $\log - \log$ scale, and the expression for a global Nusselt number can be represented by an empirical correlation:

$$\overline{Nu}_L = C Re^m Pr^n$$

- Specific values of C , m and n often are independent of the fluid, but they depend on the geometry of the surface and flow type.

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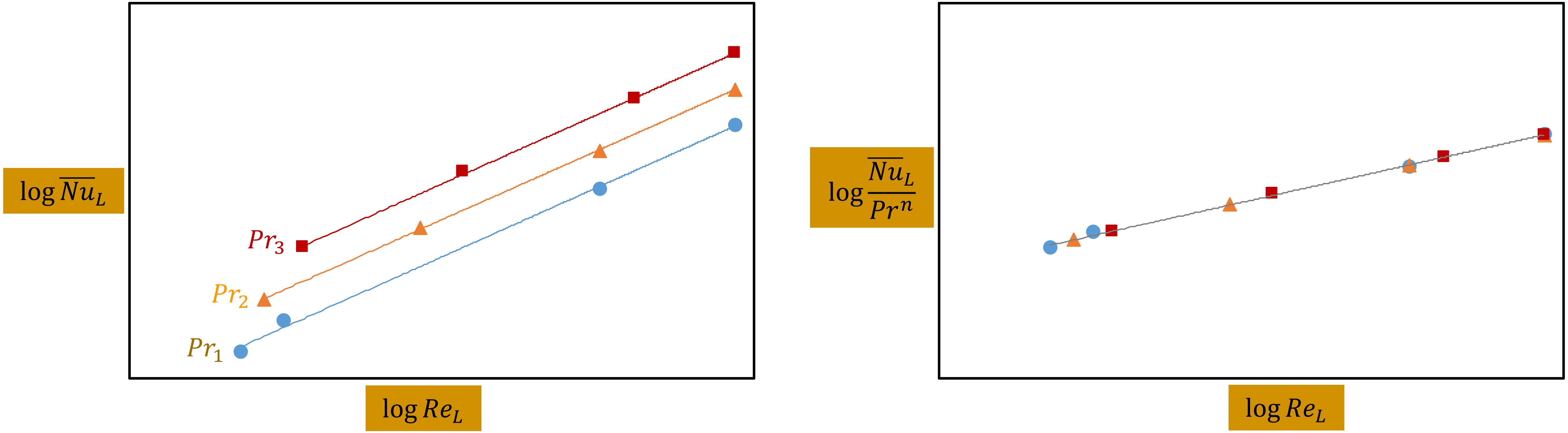
Heat Transfer Correlations (cont.)



Non-dimensional empirical correlation of heat transfer measurements

Summary

- Convection heat transfer represents the bulk motion of heat by a flowing fluid.
- Naturally, there is an intimate connection between convection and the fluid mechanics of the flow.
- The main goal of convection analysis is to determine the heat transfer (represented by the heat transfer coefficient) for a given geometry and flow field.
- In the next lesson, we will begin our study of the thermal boundary layer and its relation to the velocity boundary layer. This will give us insight into the general nature of convection physics.

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