FUNDAMENTAL OF CONVECTION

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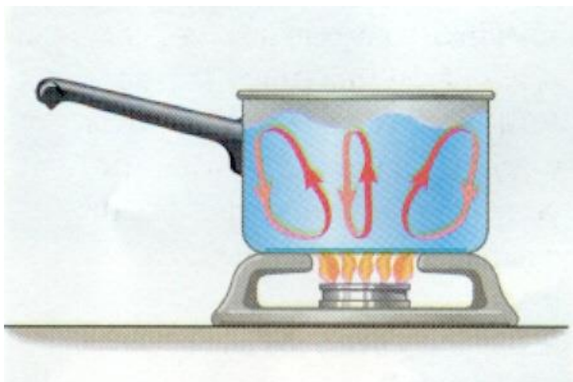
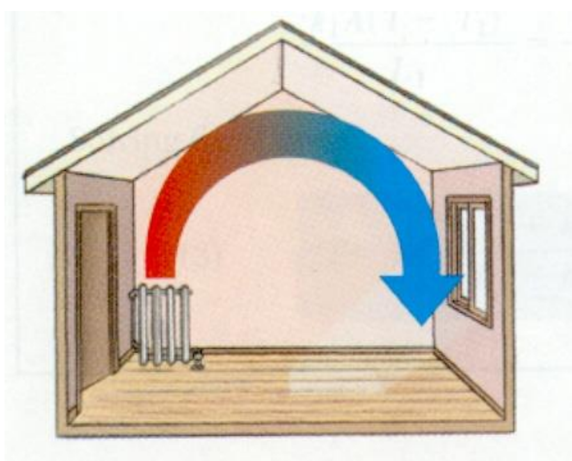
Convection

- Bulk movement of thermal energy in fluids



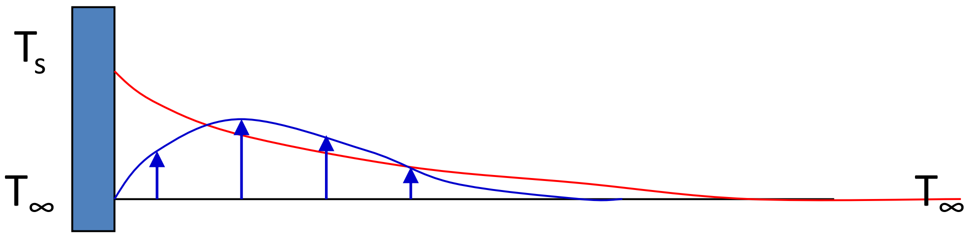


Physical Mechanism of Convection Heat Transfer

Convection is the mechanism of heat transfer between a solid surface and a pool of fluid in the presence of bulk fluid motion. It can be classified as:

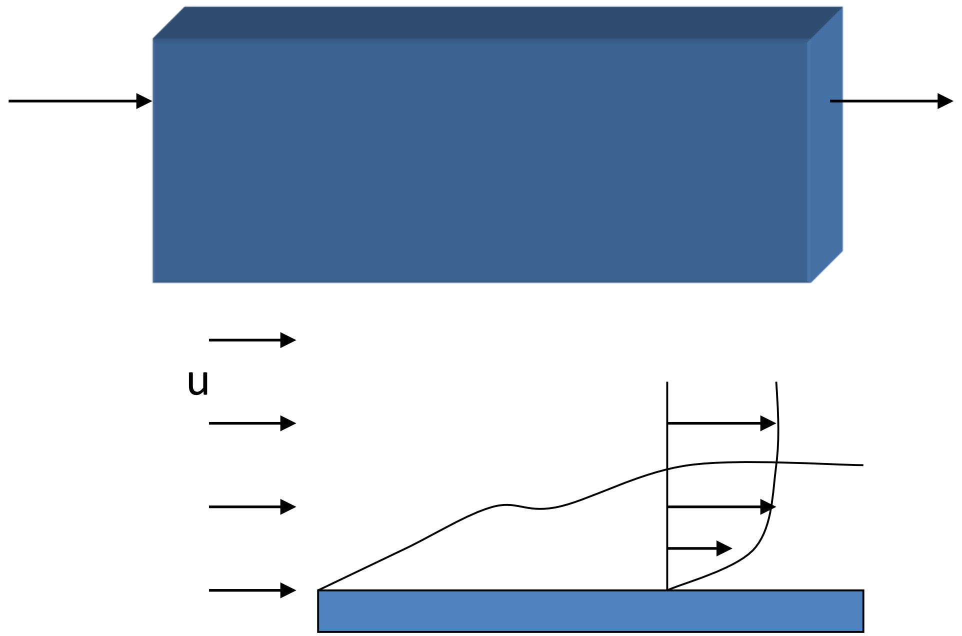
1) **Natural or free convection**:

   The bulk fluid motion is due to buoyant force caused by density gradient between the hot and cold fluid regions. The temperature & velocity distributions of free convection along a vertical hot flat surface is shown in figure below.



2) **Forced convection** :

The bulk fluid motion is caused by external means, such as a fan, a pump or natural wind, etc.



The properties of the flow fields

- Due to the properties of fluid both velocity and thermal **boundary layers** are formed. Velocity boundary layer is caused by viscosity and thermal boundary layer is caused by both viscosity and thermal conductivity of the fluid.

- Internal versus external flow

  - External flow : the solid surface is surrounded by the pool of moving fluid

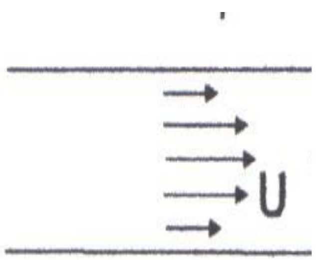
  - Internal flow : the moving fluid is inside a solid channel or a tube.

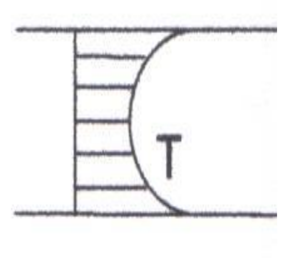
The properties of the flow fields

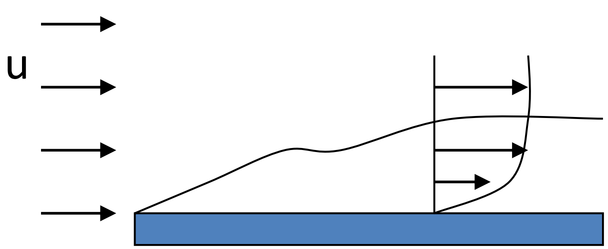
- **Laminar flow versus turbulent flow**

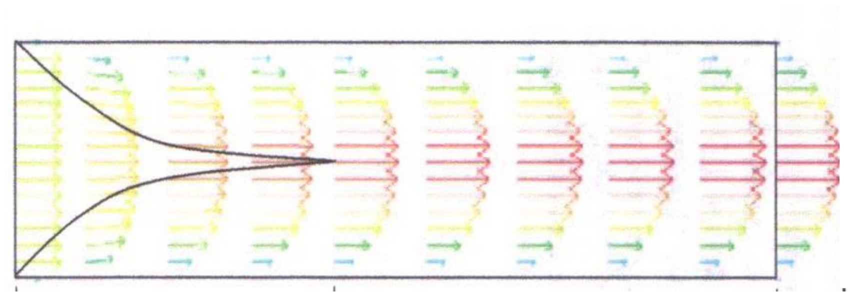
  - Laminar flow: the stream lines are approximately parallel to each other

  - Turbulent flow: the bulk motion of the fluid is superimposed with turbulence









The governing parameters of convection heat transfer

- **Newton's law of cooling**

$$\dot{Q} = hA(T_s - T_\infty)$$

- The main objective to study convection heat transfer is to determine the proper value of convection heat transfer coefficient for specified conditions. It depends on the following parameters:

  - The Bulk motion velocity, u, (m/s)
  - The dimension of the body, L, (m)
  - The surface temperature, T_s, ^{o}C or K
  - The bulk fluid temperature, T_∞ , ^{o}C or K

The governing parameters of convection heat transfer (Cont.)

- - The density of the fluid, ρ , kg/m^3
  - The thermal conductivity of the fluid, k, (W/m.K)
  - The dynamic viscosity of the fluid, μ , (kg/m.s)
  - The specific heat of the fluid, C_p , (J/kg.K)
  - The change in specific weight, $\Delta\rho g$, ($kg/(m^2s^2)$) or (N/m^3)
  - The shape and orientation of the body, S

- The convection heat transfer coefficient can be written as

$$h = f(u, L, T_s, T_\infty, \rho, k, \mu, C_p, \Delta\rho g , S)$$

- It is impossible to achieve a correlation equation for convection heat transfer in terms of 10 variables. **A better way to reduce the number of variables is required.**

- **Dimensionless analysis**

  There are 11 parameters with 4 basic units (length, m), (mass, kg), (temperature, ^{o}C or K) , and (time, s).

  Applying the method of dimensional analysis, it can be grouped into 11- 4 = 7 dimensionless groups, they are:

$$\frac{hL}{k} = F\left(\frac{\rho u L}{\mu}, \frac{\mu c_p}{k}, \frac{\rho g \Delta\rho L^3}{\mu^2}, \frac{T_s}{T_\infty}, \frac{u^2}{c_p T_\infty}, S\right)$$

1. Nusselt number : $Nu_L = \frac{hL}{k}$

2. Eckert number : $E_k = \frac{u^2}{c_p T_\infty}$

3. Reynods number : $\mathrm{Re}_L = \frac{\rho u L}{\mu}$

4. Temperature ratio : $\theta_s = \frac{T_s}{T_\infty}$

5. Grashof number : $Gr_L = \frac{\rho g \Delta\rho L^3}{\mu^2}$

6. S : shape of the surface

7. Prandtl number : $\mathrm{Pr} = \frac{\mu c_p}{k}$

- **To find Reynolds number**
  Choosing density (ρ), dimension (L), surface temperature (T_s), and dynamic viscosity (μ) as the 4 basic parameters, and velocity (u) as the input parameter. The dimensionless number is obtained by solving the 4 constants, a, b, c, & d.

$$\rho^a L^b T_s^c \mu^d u = 0$$

$$(\frac{kg}{L^3})^a (L)^b ({}^oC)^c (\frac{kg}{sL})^d \frac{L}{s} = \pi_1$$

$$L \Rightarrow -3a + b - d + 1 = 0$$

$$kg \Rightarrow a + d = 0$$

$${}^oC \Rightarrow c = 0$$

$$s \Rightarrow -d - 1 = 0$$

$$d = -1, c = 0, a = 1, b = 1$$

$$\frac{\rho L u}{\mu} = \pi = \mathrm{Re}_L$$

- **Simply the dimensionless equations**

Now we have reduced the equation involving 11 variables into a 7 dimensionless group equation. However, 7 dimensionless groups is still too large, we need neglecting the unimportant dimensionless groups. Eckert number is important for high speed flow. It can be neglected for our application. If the average fluid temperature is used for getting the fluid properties, the temperature ratio can also be discarded. After neglecting the two unimportant dimensionless groups, the general convection equation is

$$Nu_L = F(\mathrm{Re}_L, \mathrm{Pr}, Gr_L, S)$$

Forced convection: the density change is very small, the Grashof number is neglected

$$Nu_L = F(\mathrm{Re}_L, \mathrm{Pr}, S)$$

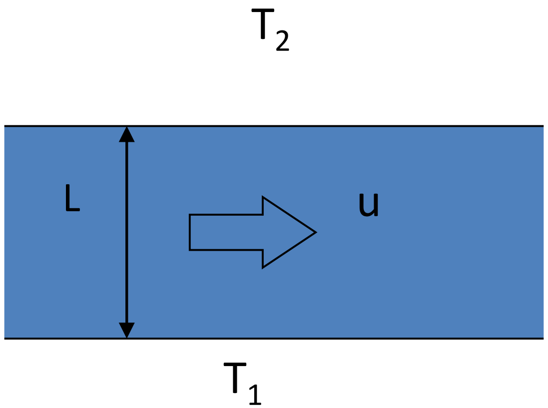
- Natural convection: there is no bulk fluid motion induced by external means, u = 0, Reynolds number is disappeared.

$$Nu_L = F(Gr_L, \mathrm{Pr}, S)$$

The Physical Meaning of The Dimensionless Numbers

- **Nusselt number**

It is the ratio of convection heat transfer rate to the conduction heat transfer rate. Consider an internal flow in a channel of height L and the temperatures at the lower and upper surfaces are T_1 & T_2, respectively.



The convection heat transfer rate is

$$\dot{Q}_{\mathrm{cov}} = hA(T_1 - T_2)$$

The conduction heat transfer rate is

$$\dot{Q}_{cond} = \frac{kA}{L}(T_1 - T_2)$$

The ratio

$$Nu_L = \frac{\dot{Q}_{\mathrm{cov}}}{\dot{Q}_{cond}} = \frac{hA}{\frac{kA}{L}} = \frac{hL}{k}$$

- **The Reynolds number**

It is the ratio of inertia force to viscous force of the moving fluid.

- Inertia force

$$F_i = ma = \rho L^3 \frac{L}{s^2} = \rho L^2 (\frac{L}{s})^2 = \rho L^2 u^2$$

- The viscous force

$$F_v = \tau A = \mu \frac{\Delta u}{\Delta y} L^2 = \mu \frac{u}{L} L^2 = \mu u L$$

- The ratio

$$\mathrm{Re}_L = \frac{\rho u L}{\mu} = \frac{uL}{\frac{\mu}{\rho}} = \frac{uL}{\nu}$$

- **The Prandtl number**

It is the ratio of the momentum diffusivity to the thermal diffusivity. Thermal difusivity controls how fast the heat diffuses in a medium. It has the form

$$\alpha = \frac{k}{\rho c_p}$$

The momentum diffusivity is the kinematic viscosity and it controls the rate of diffusion of momentum in a fluid medium. The ratio of the two is called Prandtl number.

$$\Pr = \frac{\upsilon}{\alpha} = \frac{\frac{\mu}{\rho}}{\frac{k}{\rho c_p}} = \frac{\mu c_p}{k}$$

- ## The thermal expansion coefficient

It is defined as

$$\beta = -\frac{1}{\rho}(\frac{\partial \rho}{\partial T})_p$$

The negative sign results from the fact that, for gases, the change of density with respect to temperature under constant pressure process is always negative. From ideal gas law

$$p = \rho RT \Rightarrow dp = \rho RdT + RTd\rho = 0 \longrightarrow (\frac{d\rho}{dT})_p = -\frac{\rho}{T} \longrightarrow \beta = \frac{1}{T}$$

For ideal gas, the thermal expansion coefficient is the inverse of the absolute temperature

- ## Grashof number

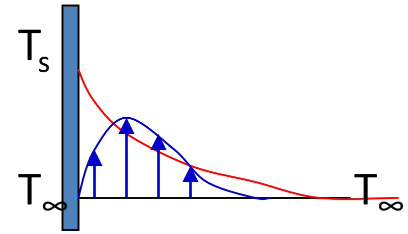
The Grashof number represents the ratio of the buoyant force to the viscous force.

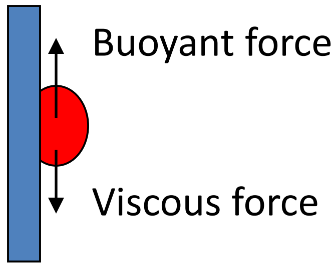
$$Gr = \frac{g\Delta\rho L^3}{\upsilon^2 \rho}$$

- **Grashof number**

  The change of density is

$$\Delta\rho = -\rho\beta\Delta T = \rho_\infty - \rho = -\rho\beta(T_\infty - T) = \rho\beta(T - T_\infty)$$





Substituting into Grashof number

$$Gr_L = \frac{g\Delta\rho L^3}{\upsilon^2\rho} = \frac{g\rho\beta(T - T_\infty)L^3}{\upsilon^2\rho} = \frac{g\beta(T - T_\infty)L^3}{\upsilon^2}$$

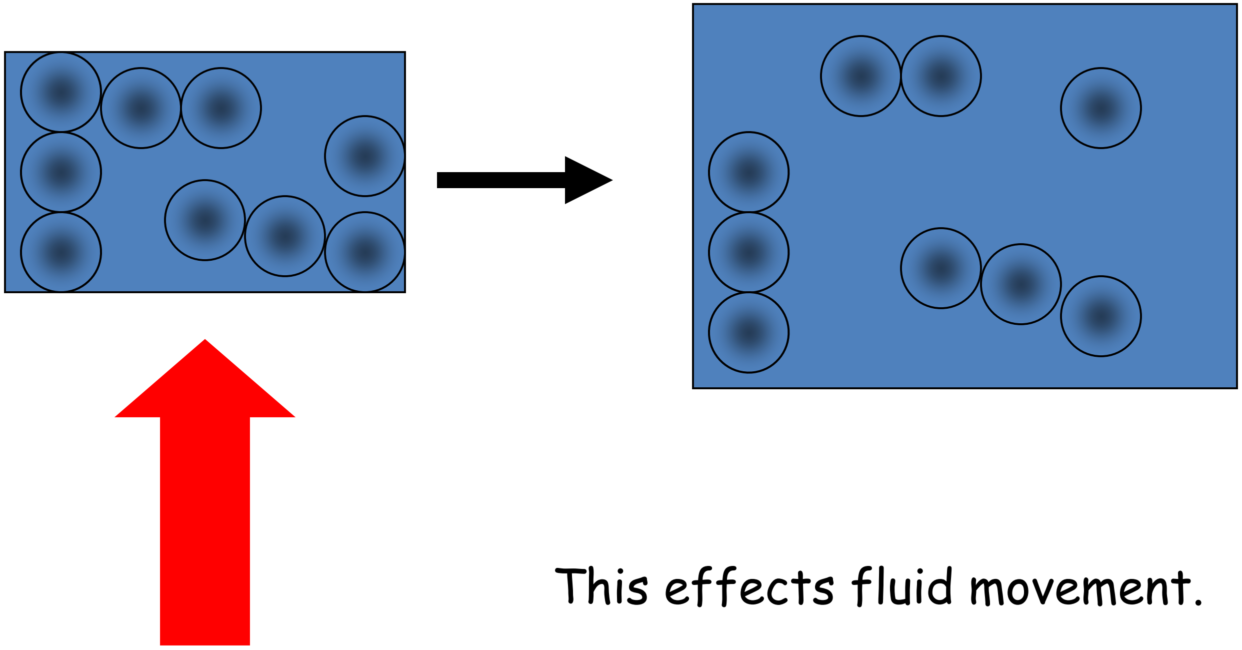
The subscript *L* means that the characteristic length of the Grashof number. It may be the length of the surface. For ideal gas, Gr_L is

$$Gr_L = \frac{g(T - T_\infty)L^3}{\upsilon^2 T}$$

Convection

What happens to the particles in a liquid or a gas when you heat them?

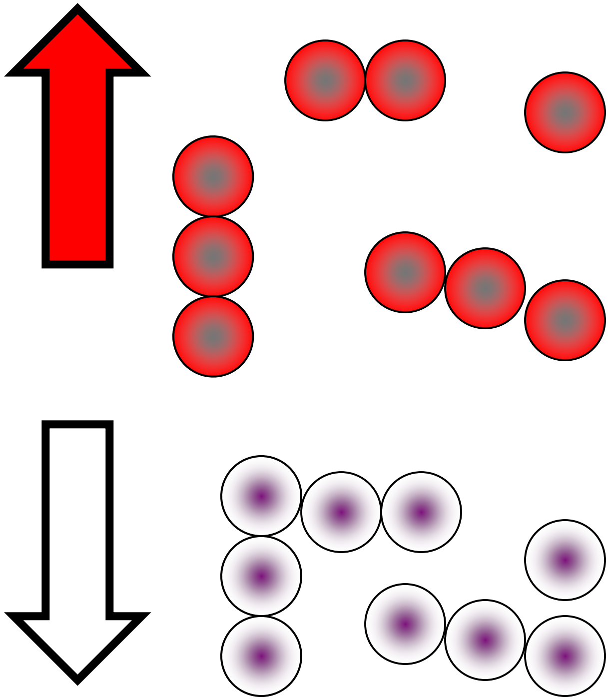
The particles spread out and become less dense.



This effects fluid movement.

Fluid movement

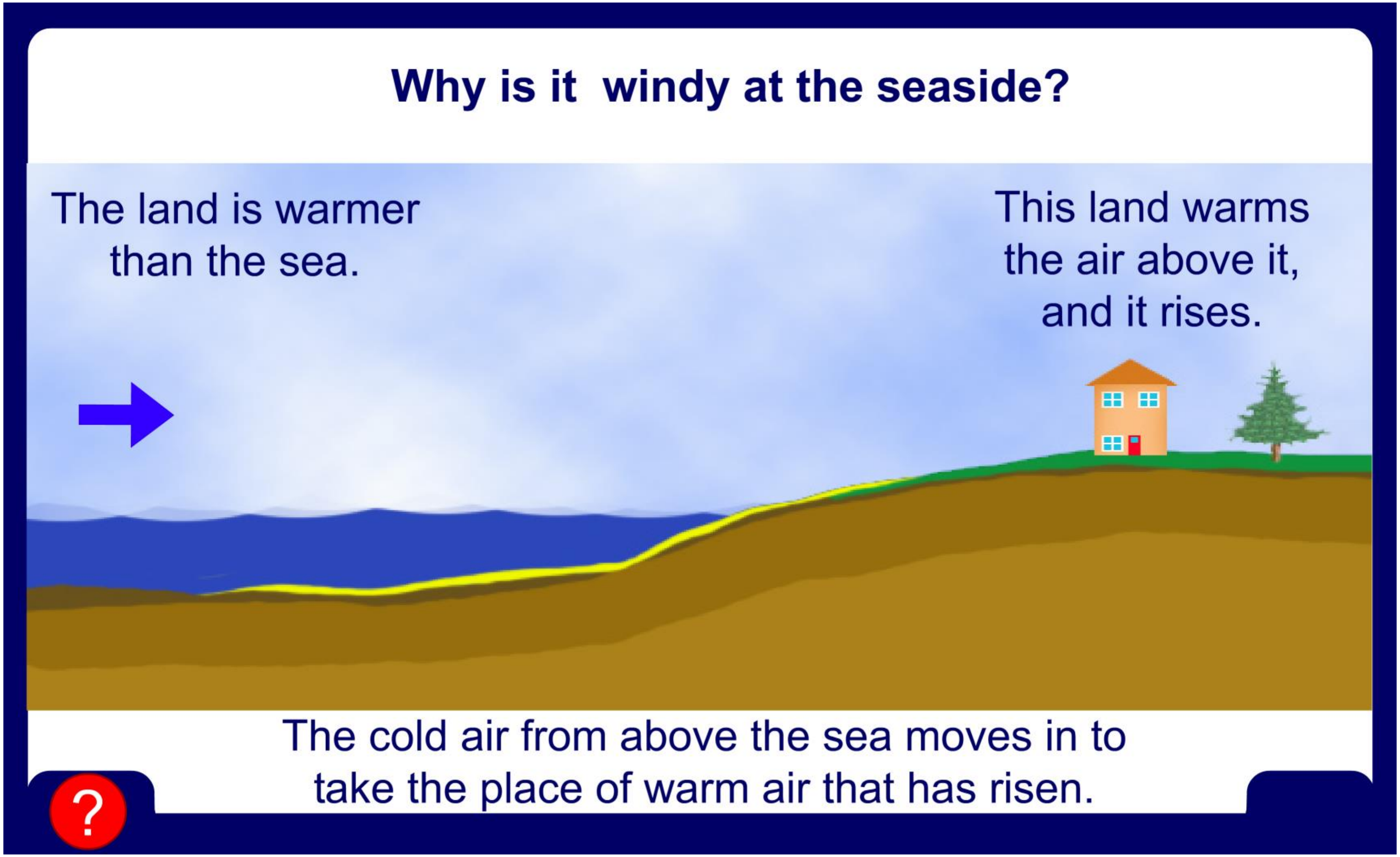
Cooler, more dense, fluids sink
through warmer, less dense fluids.



In effect, warmer liquids and gases rise up.

Cooler liquids and gases sinks

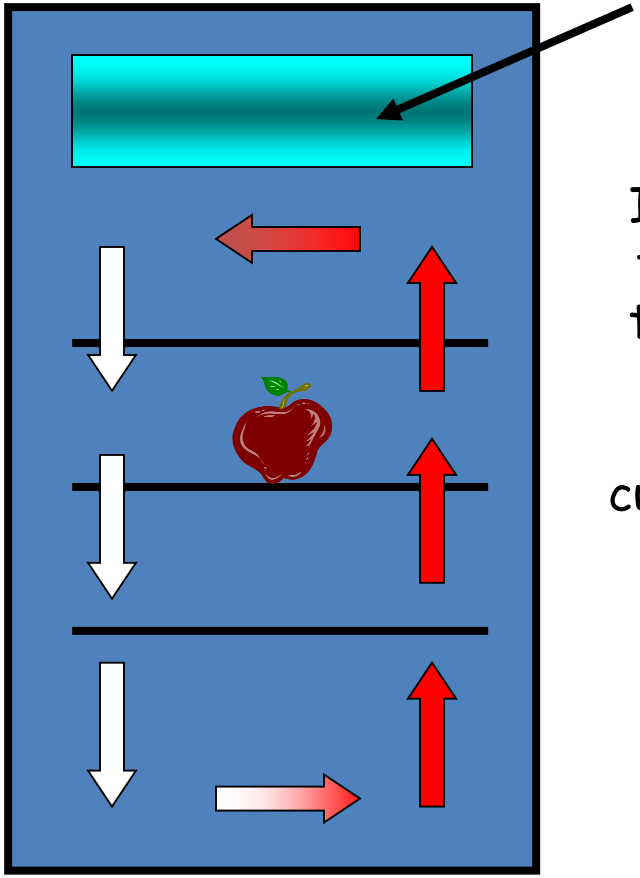
Why is it windy at the seaside?



Cold air sinks

Where is the freezer compartment put in a fridge?

It is put at the top, because cool air sinks, so it cools the food on the way down.



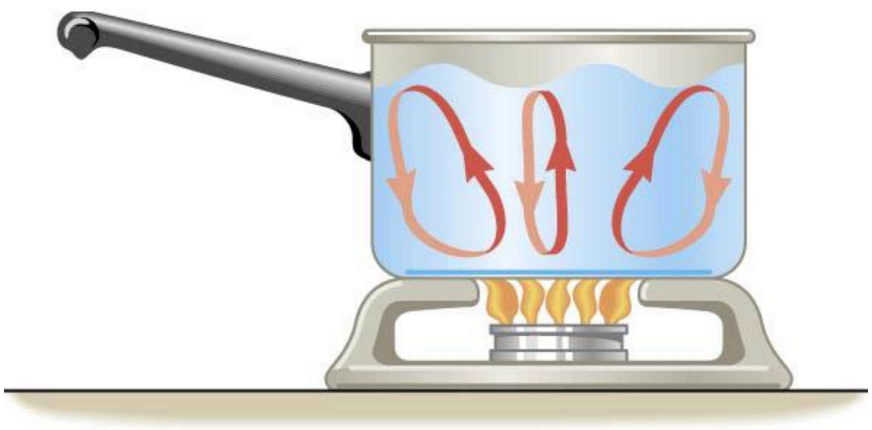
Freezer compartment

It is warmer at the bottom, so this warmer air rises and a convection current is set up.

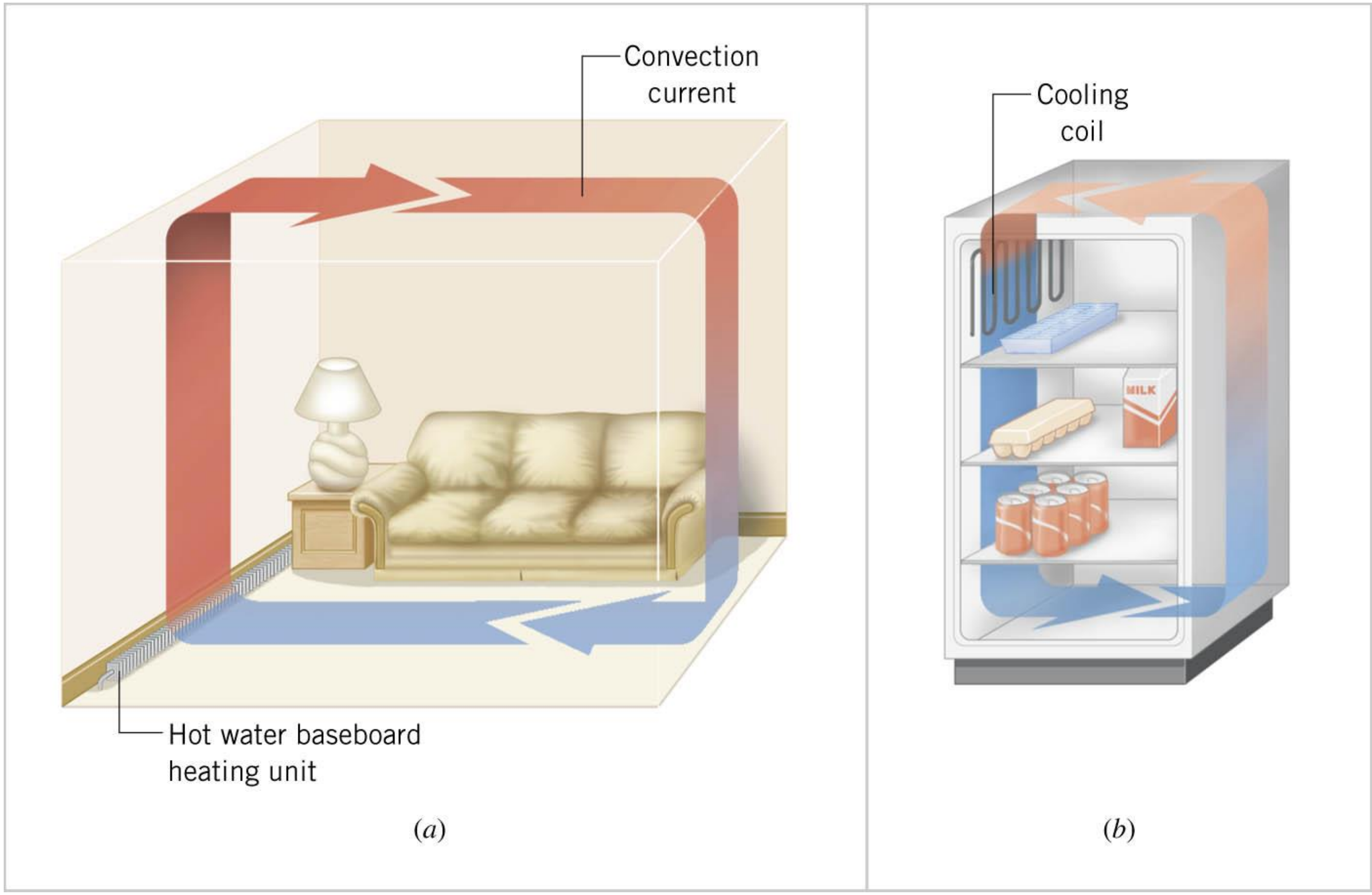
Convection

Convection is the process in which heat is carried from place to place by the bulk movement of a fluid.

Convection currents are set up when a pan of water is heated.

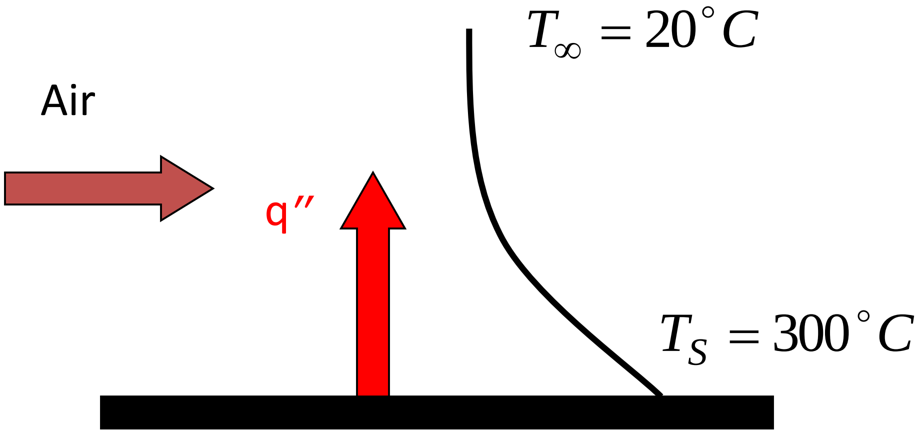


Hot Water Baseboard Heating and Refrigerators



Convection

Air at 20°C blows over a hot plate, which is maintained at a temperature T_s=300°C and has dimensions 20x40 cm.



The convective heat flux is proportional to

$$q_x'' \propto T_S - T_\infty$$

- The proportionality constant is the *convection heat transfer coefficient*, h ($W/m^2.K$)

$$q_x'' = h(T_S - T_\infty)$$

Newton's law of Cooling

- For air h=25 $W/m^2.K$, therefore the heat flux is $q_x'' = 7{,}000\ W/m^2$
- The ***heat rate***, is $q_x = q_x''.\ A = q_x''.\ (0.2 \times 0.4) = 560$ W.
- In this solution we assumed that heat flux is positive when heat is transferred from the surface to the fluid
- *How would this value change if instead of blowing air we had still air (h=5 $W/m^2.K$) or flowing water (h=50 $W/m^2.K$)*

The End

Terima kasih

REFERENCES

1. **Sinaga, Nazaruddin**. *Numerical Modeling of A Coal Briquette During Ignition and Combustion*, Proceeding, The 9th International Symposium on Transport Phenomenena, Singapore, 1996.
2. **Sinaga, Nazaruddin**. *Perkembangan Heat Transfer Enhancement pada Alat Penukar Kalor*, Majalah Rotasi, Jurusan Teknik Mesin Fakultas Teknik Undip, Vol. 2 No.2, April, 2000.
3. **Sinaga, Nazaruddin**. *Refrigeration By Using Coal Briquet As an Alternative Energy*, Proceeding, The 3rd International Conference and Exhibition on Energy, Yogyakarta, 29-31 Juli 2002
4. **Sinaga, Nazaruddin, A. Suwono, Sularso, and P. Sutikno**. *Simulation of Fin Arrangement Effect on Performance of Staggered Circular Finned-Tube Heat Exchanger*, Proceeding, International Conference on Fluid and Thermal Energy Conversion, Bali, 2003
5. **Sinaga, Nazaruddin, A. Suwono, Sularso, and P. Sutikno**. *Kaji Numerik dan Eksperimental Pembentukan Horseshoe Vortex pada Pipa Bersirip Anular*, Prosiding, Seminar Nasional Teknik Mesin II, Universitas Andalas, Padang, Desember 2003
6. **Sinaga, Nazaruddin, A. Suwono dan Sularso**. *Pengamatan Visual Pembentukan Horshoe Vortex pada Susunan Geometri Pipa Bersirip Anular*, Prosiding, Seminar Nasional Teknik Mesin II, Universitas Andalas, Padang, Desember 2003.
7. **Sinaga, Nazaruddin**. *Pengukuran Intensitas Turbulensi pada Susunan Sebaris dan Dua Baris Pipa Bersirip Lingkaran Menggunakan Laser Doppler Velocimeter*, Majalah Reaktor, Jurusan Teknik Kimia FT-Undip, Vol. 9 No. 1, Juni, 2005.
8. **Sinaga, Nazaruddin**. *Pengaruh Parameter Geometri dan Konfigurasi Berkas Pipa Bersirip Anular Terhadap Posisi Separasi di Permukaan Sirip*, Jurnal Ilmiah Poros, Jurusan Teknik Mesin FT Universitas Tarumanegara, Vol. 9 No. 1, Januari, 2006.
9. **Sinaga, Nazaruddin**. *Pengaruh Model Turbulensi Dan Pressure-Velocity Copling Terhadap Hasil Simulasi Aliran Melalui Katup Isap Ruang Bakar Motor Bakar*, Jurnal Rotasi, Volume 12, Nomor 2, ISSN:1411-027X, April 2010.
10. **Sinaga, Nazaruddin, dan M. H. Sonda**. *Pemilihan Kawat Enamel Untuk Pembuatan Selenoid Dinamometer Arus Eddy Dengan Torsi Maksimum 496 Nm*, Eksergi, Jurnal Teknik Energi Vol 9 No.1 Januari 2013.

11. **Sinaga, Nazaruddin dan S. J. Purnomo**. *Hubungan Antara Posisi Throttle, Putaran Mesin dan Posisi Gigi Terhadap Konsumsi Bahan Bakar pada Beberapa Kendaraan Penumpang*, Eksergi, Jurnal Teknik Energi, Vol.9 No. 1, Januari 2013.
12. **Sinaga, Nazaruddin**. Pelatihan Teknik Mengemudi Smart Driving Untuk Menurunkan Emisi Gas Rumah Kaca Dan Menekan Biaya Transportasi Angkutan Darat, Prosiding, Seminar Nasional Teknik Mesin XII (SNTTM XII), Fakultas Teknik Universitas Lampung, Oktober 2013.
13. **Sinaga, Nazaruddin, S. J. Purnomo dan A. Dewangga**. *Pengembangan Model Persamaan Konsumsi Bahan Bakar Efisien Untuk Mobil Penumpang Berbahan Bakar Bensin Sistem Injeksi Elektronik (EFI)*, Prosiding, Seminar Nasional Teknik Mesin XII (SNTTM XII), Fakultas Teknik Universitas Lampung, Oktober 2013.
14. **Yunianto, Bambang dan N. Sinaga**. Pengembangan Disain Tungku Bahan Bakar Kayu Rendah Polusi Dengan Menggunakan Dinding Beton Semen, Majalah Rotasi, Volume 16, Nomor 1, Januari 2014, ISSN:1411-027X.
15. **Nazaruddin Sinaga, Abdul Zahri.** *Simulasi Numerik Perhitungan Tegangan Geser Dan Momen Pada Fuel Flowmeter Jenis Positive Displacement Dengan Variasi Debit Aliran Pada Berbagai Sudut Putar Rotor*, Jurnal Teknik Mesin S-1, Vol. 2, No. 4, Tahun 2014.
16. **Nazaruddin Sinaga**. *Kaji Numerik Aliran Jet-Swirling Pada Saluran Annulus Menggunakan Metode Volume Hingga*, Jurnal Rotasi Vol. 19, No. 2, April 2017.
17. **Nazaruddin Sinaga**. *Analisis Aliran Pada Rotor Turbin Angin Sumbu Horisontal Menggunakan Pendekatan Komputasional*, Eksergi, Jurnal Teknik Energi POLINES, Vol. 13, No. 3, September 2017.
18. **Syaiful, Sinaga, N., Wulandari, R., Bae, M.W**. *Effect of Perforated Concave Delta Winglet Vortex Generators on Heat Transfer Augmentation of Fluid Flow Inside a Rectangular Channel: An Experimental Study*. International Mechanical and Industrial Engineering Conference 2018 (IMIEC 2018), MATEC Web of Conferences Vol.204 , 2018 , 21-Sep-18 , EDP Sciences 12 , ISSN: 2261-236X
19. **Muchammad, M., Sinaga, N., Yunianto, B., Noorkarim, M.F., Tauviqirrahman, M.** *Optimization of Texture of The Multiple Textured Lubricated Contact with Slip*, International Conference on Computation in Science and Engineering, Journal of Physics: Conf.

Series 1090-012022, 5 November 2018, IOP Publishing, Online ISSN: 1742-6596 Print ISSN: 1742-6588.

20. **Nazaruddin Sinaga, Mohammad Tauiviqirrahman, Arif Rahman Hakim, E. Yohana.** *Effect of Texture Depth on the Hydrodynamic Performance of Lubricated Contact Considering Cavitation*, Proceeding of International Conference on Advance of Mechanical Engineering Research and Application (ICOMERA 2018), Malang, October 2018.
21. **Syaiful, N. Sinaga, B. Yunianto, M.S.K.T. Suryo**. *Comparison of Thermal-Hydraulic Performances of Perforated Concave Delta Winglet Vortex Generators Mounted on Heated Plate: Experimental Study and Flow Visualization*, Proceeding of International Conference on Advance of Mechanical Engineering Research and Application (ICOMERA 2018), Malang, October 2018.
22. **Nazaruddin Sinaga, Syaiful, B. Yunianto, M. Rifal**. Experimental and Computational Study on Heat Transfer of a 150 KW Air *Cooled Eddy Current Dynamometer*, Proc. The 2019 Conference on Fundamental and Applied Science for Advanced Technology (Confast 2019), Yogyakarta, Januari 21, 2019.
23. **Nazaruddin Sinaga**. *CFD Simulation of the Width and Angle of the Rotor Blade on the Air Flow Rate of a 350 kW Air-Cooled Eddy Current Dynamometer*, Proc. The 2019 Conference on Fundamental and Applied Science for Advanced Technology (Confast 2019), Yogyakarta, Januari 21, 2019.
24. **Anggie Restue, Saputra, Syaiful, and Nazaruddin Sinaga**. *2-D Modeling of Interaction between Free-Stream Turbulence and Trailing Edge Vortex*, Proc. The 2019 Conference on Fundamental and Applied Science for Advanced Technology (Confast 2019), Yogyakarta, January 21, 2019.