TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Mechanical Engineering

Heat transfer in horizontally oriented air enclosure

Master Thesis

Study programme: N2301 Mechanical Engineering
Study branch: Machines and Equipment Design

Author: **Gowtham Ananthasayanan**
Thesis Supervisors: doc. Ing. Jaroslav Šulc, CSc.
Department of Power Engineering Equipment

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Master Thesis Assignment Form

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Determination of the criterial equation for calculation of Nusselt number for convective heat transfer in horizontal enclosure. To this purpose experimental flux determination of the total heat horizontally oriented air enclosures will be performed by means of the heat flow meter HFM/436/3/1. Experimentally obtained values of the total heat flux will be compared with analytically calculated contributions of heat transfer by conduction and radiation in enclosures.

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June 7, 2020 Gowtham Ananthasayanan

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Abstract

The aim of this thesis was to verify the applicability in the professional literature reported relations for the calculation of the heat transfer in the right, horizontally oriented air enclosure on the basis of the results of measurements carried out using the HFM 436/3/1E Lambda measuring device. The air enclosures were created using square polystyrene boards, in which coaxial square holes of the size corresponding to the location and size of the heat flow sensors built into the upper and lower thermostatized plate of the measuring device were created. Polystyrene boards were inserted between these thermostatized plates, creating enclosures with different thicknesses of the air layer. The temperature difference inserted on the thermostatic plates caused the heat flow through the assembly.This heat flow along with this temperature difference and the thickness of the air layer, made it possible to calculate the quantities needed to determine the relevant criterial equation. The relatively large thickness of the vertical walls of the cavity allowed to consider their surface to be "reemiting", which allowed the analytical determination of the radiant component of heat flux through the enclosure.

Keywords

Conduction, Convection, Radiation, Emissivity, View factor, Reciprocity rule, Summation rule, Effective thermal conductivity, HFM 436 Lambda, Q Lab software, Thermocouple, Dimensionless numbers, Reradiating surface.

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k	Thermal Conductivity	W/m. K
Δt	Temperature Difference	K
m	Mass	kg
h	Heat Transfer Coefficient	W/m^2. K
A	Area	m^2
Cp	Specific Heat Capacity	J/kg. K
ε	Emissivity	1
T∞	Temperature of the Fluid	K
C	Fluid Velocity	m/s
υ	Kinematic Viscosity	m^2 /s
β	Co-efficient of Volume of Expansion (1/K)	
L	Characteristic Dimension	m
P	Density	kg/m^3
ɑ	Thermal Diffusivity	m^2/s
t	Time	s
λ	Wavelength	μm

CHAPTER – 1

1. INTRODUCTION

The transfer of heat energy from one object to another object is called Heat transfer. This heat transfer has different modes of mechanism. In this thesis, we are going to discuss about the determination of criterial equation for Nusselt number calculation for convective heat transfer in rectangular air enclosure. In the past, the equation has been given based on numerical and analytical method. Now, the experimental determined equation will be compared and verified with the numerical and analytical methods. This experiment is carried out on a measuring device HFM 436/3/1E Lambda. This instrument is used to measure the co efficient of thermal conductivity of solid insulating materials. The experimental setup is made and a series of measurements of heat flux will be taken to find the criterial equation. Calculations related with heat transfer mechanism will be carried out and thus it compared and verified.

CHAPTER – 2

2.1 HEAT TRANSFER

Heat transfer is the flow of heat from hot body to cold body. In other terms from higher temperature to lower temperature. In the early days in history, scientist imagined all bodies contained a fluid which is not visible and they called it caloric. It has assigned various properties and some of them are not proved to be consistent with the nature. Scientist thought that caloric was important feature to think of heat.

In the mid of nineteenth century, it was thought to be wrong to consider that, caloric flowing from hot objects to cold objects as the laws of thermodynamics figured. The fundamental object for the laws of thermodynamics is heat and temperature. These laws are as follows

First law of thermodynamics

"*It states that energy can be neither created nor destroyed as it can change its nature of form.*" Hence this cannot be proved mathematically but no things in nature violated the law.

Second law of thermodynamics

Kelvin-Planck's statement – it states it is impossible for an object to perform a work without heat is being rejected from hot body to cold body.

Clausius statement – it states that it is impossible to transfer heat from a cold body to hot body unless some work is done.

Third law of thermodynamics

The randomness and disorderness in nature is called Entropy. The entropy of universe is increasing as the energy of universe is decreasing.[1]

2.1.1 Modes of Heat Transfer

The classification of heat transfer is of three ways as follows,

- Conduction
- Convection
  - Forced convection
  - Free convection
  - Phase transformation
- Radiation

2.2 CONDUCTION

The energy cease doing by the microscopic particles such as atoms and molecules of hot region of a body to cold regions is known as heat. Conduction is one of the mode of heat transfer, in solids or in fluids by exchange of energy from a hot region to cold region due to the gradient of temperature present in it. Once the distribution of temperature is determined as a function of position and time, then the heat flow in a body can be evaluated from the laws of heat flow to the gradient of temperature i.e. for example if one end of the iron rod is heated up after some time the heat is transferred to the other end this action is done by the atoms which are transferring the heat from one to other end. The principal behind the conduction is quantifying the temperature gradient within a solid body.

The law gives the relationship between the temperature gradient and heat flow, thus it was given on the based on experiments and named after physicist Joseph Fourier. Hence the law is given as in equation – 1.

$$\dot{Q} = -\mathrm{k}\,.\,\mathrm{A}.\left(\frac{\mathrm{dT}}{\mathrm{dX}}\right)\ [\mathrm{W}] \tag{1}$$

Where, $\dot{Q}$ – Heat flux W

k- Thermal Conductivity W/m^2. K

$\frac{dT}{dX}$- Temperature Difference K

From the above equation, the heat transfer is directly proportional to thermal conductivity of the specific material. Hence co efficient of thermal conductivity is an important factor for rate of flow of heat. For different types of materials, the co-efficient of thermal conductivity is different has the change in valence and crystal structure. Metals have high value and then goes with liquid metals and gaseous so on.

For metals the thermal conductivity increase with decrease in temperature and for gases the conductivity increase with increase in temperature and in insulating materials the conductivity increase with increase with the temperature. At temperature equals to zero the conductivity of the materials significantly increases.

In conduction there are number of parameters to calculate, in order to reduce the parameters, we define the problem by some dimensionless numbers such as Biot number, Fourier Number.

Lumped system analysis

In the analysis of heat transfer some bodies are figured to behave like lump whose inner temperature remains uniform in all the time during the process of heat transfer. Such bodies temperature is taken to be a function of time T(t). the analysis of heat transfer utilizes the idealization is called Lumped system analysis.

Consider a arbitrary shape of mass m, volume V, area A, density ρ, and specific heat capacity Cp, the initial temperature is Ti at t=0, the object is placed in to a medium of temperature T∞ and transfer of heat takes place between the object and surroundings with the coefficient of heat transfer h. we will assume that $T_\infty > T_i$ and also the analysis valid for vice versa. So that the uniform temperature remains in the object and change with time dt.

The balance of energy of the solid for the interval of time dt can is expressed as

[Heat transfer in to the object during dt] = [Energy increase in the object during dt]

$$hA\,(T\infty - T) = mCp\,dT \qquad (2)$$

Transient Heat conduction in plane walls, cylinders, sphere

In this section we assume that temperature variation with time and position in 1D problems such as plane, cylinders, sphere. A plane wall of thickness L, cylinder of radius r and sphere with radius r and uniform initial temperature T. At t = 0, each geometry placed in to a medium with temperature T∞. now heat transfer takes place between these geometry and surroundings with steady and constant coefficient of heat transfer h. since all the geometries are thermally symmetry; plane wall is symmetric about its center at x = 0, cylinder in center point r = 0, and sphere with center point r = 0. We neglect heat transfer by radiation between these geometries and their surroundings.[2]

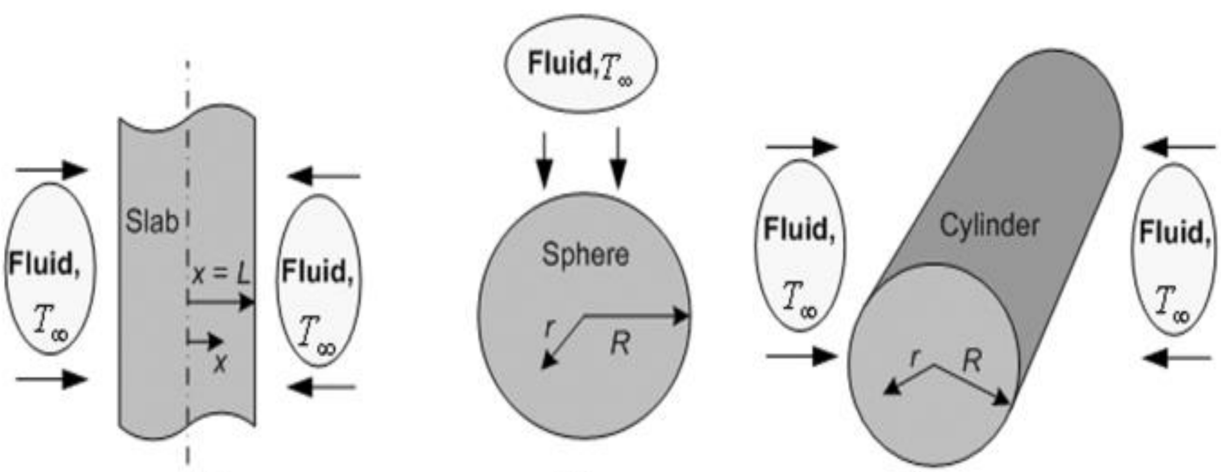

Figure 1: Transient heat conduction in plane wall, sphere, cylinder.**[3]**

2.3 CONVECTION

Convective heat transfer is process of combination of microscopic and macroscopic involvement of motion and fluid flow i.e. microscopic motion of conduction and macroscopic fluid flow. Convection occurs when the fluid flow is surfaced in a wall which is transferring heat between the wall surface and fluid flow above the wall, hence this layer is called thermal boundary layer.

Although, the process of heat transfers between the wall and the fluid is complicated, newton has figured the relationship between the wall and flow of fluid it is given as,

$$Q = h\,(Ts - T\infty) \qquad [W/m^2] \tag{3}$$

Where,

h- Convection heat transfer co-efficient W/m^2. K

Ts- Temperature of the surface K

T∞ - Temperature of the fluid K

Where h, is the heat transfer co- efficient, which involves a complex heat transfer process. The value depends of the different properties of the material, mechanical, geometrical. Convective heat transfer is of different types; heat can be transferred by either free or forced way. It can also have classified based on internal and external flow of fluid.[4]

2.3.1 Classification of Fluid flow

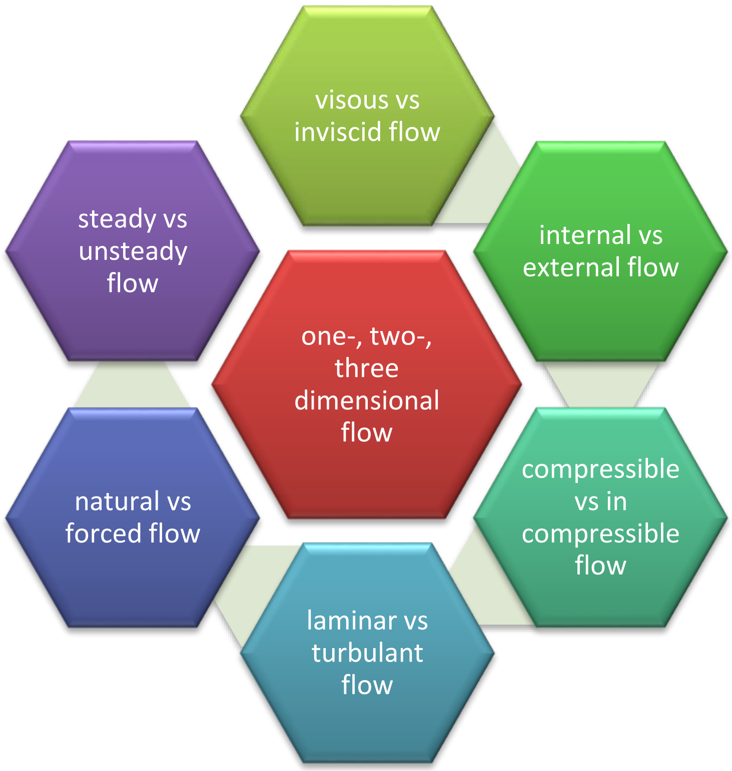

Figure 2: Classification of Fluid Flow Source[own]

Viscous vs inviscid flow

A fluid with more internal resistance which in turns slow down the motion of itself is called viscosity, which is used to measure the internal stickiness of the fluid. In liquids it is caused by the cohesive forces and in gases it is caused by the molecular collisions. Thus there is no fluid is with viscosity zero. When the effects of viscosity of flow is more, then the fluid is viscous in nature. And the effects almost negligible without more loss is inviscid flow.

Internal vs external flow

When a fluid is flow in a confined space which is covered in all sides by walls or boundaries is internal flow. In this flow fluid is flow in a water flow in pipe. The liquid flow in pipe is known as open channel flow if the pipe is filled with a partial liquid and free surface in it. The flow of water in the rivers is an example for open channel flow. In other a flow which is unbounded by the flow of forced to a confined space is external flow. Such as fluid flow over a surface of a wall or a wire.

Compressible flow vs incompressible flow

Depending on the variation of density of the fluid during the flow compressible and incompressible flow are being classified. Liquids are usually incompressible since it is essentially constant in nature. For instance, a pressure of 210 atm. will cause the change in water density by 1 percent. On the other hand, gases are compressible. A pressure of 0.01 change can cause the change of about 1 percent of air density. Flow of gas is however treated as incompressible if the 5 percent of density changes, which usually cause velocity flow less than by 30 percent of sound velocity of gas.

Laminar flow vs turbulent flow

Laminar flow is the flow which is motion of fluid is smooth lines of stream. Oil is with high viscosity, which when flow in a low velocity it acts as laminar flow. Turbulent flow fluid motion is highly disordered fluid motion and it occurs in high velocities which are characterized by velocity fluctuations. The low viscosity fluid which flow in a high velocity is known as turbulent flow.

Natural vs forced flow

Depending upon the fluid motion a flow is characterized as natural flow or forced flow. In forced flow the fluid flow is initiated by means of some external source like pump, fan. Thus the motion is forced in a particular desired way. In natural flow, the motion of fluid is due to buoyancy effect thus the fluid moves from one place to another which manifests itself in rise of warmer fluid to cooler fluid flow.

Steady vs unsteady flow

In engineering the terms uniform and steady are frequently used. The term steady means no change with time in a process. While the unsteady is opposite of it with changes on time in a process. Devices such as turbines, compressors, boilers, condensers, and heat exchangers are operating for same conditions for long period of time and they are considering as steady flow devices. The fluid properties changes from point to point during a steady flow in a device, at any fixed point they remain constant.

One, two, three dimensional flow

Velocity distribution is the best characterization of a flow field and hence the flow is said to be one, two, three, dimensional flows if primarily flow velocity varies in all one, two, three dimensions respectively. In a three dimensional geometry a velocity may vary in three dimensional rendering of the flow three dimensional. The variation in velocity of flow in certain direction can be small relative in other direction. Usually in a circular pipe the fluid flow is considering as one dimensional since the variation of velocity in radial direction and not in angular or z axis. For convenience of calculation the velocity can be assumed uniform and constant across section.[4]

2.3.2 Velocity boundary layer

Consider a fluid is flowing in parallel plate in a surface. In some cases, slight contoured surface of turbine is also considered as the flat plate for accuracy purposes. The plate surface is measured in the x axis from the leading edge of the plate in flow direction, y axis is measured from the surface in perpendicular direction. The plate in x direction of fluid approaches in uniform velocity, which is equally same to the free stream velocity over the plate away from the surface.

We assume that fluid consists of adjacent layer of piles on top of each other. The velocity of first layer is zero because of no slip condition. This motionless layer slow down the neighboring fluid layer particles as a result of friction between the two layers. Then the subsequent fluid layers slow down the molecules in the next one. At some distance from the plate beyond which the free stream velocity of presence of plate remains unchanged.[4] It can be shown as,

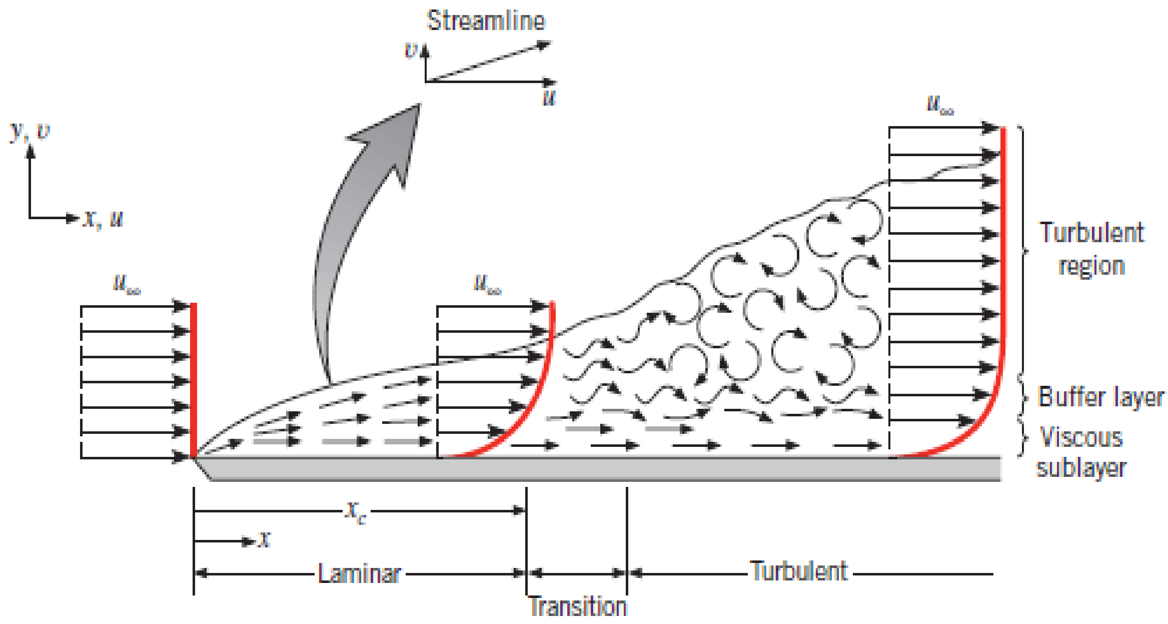

Figure 3: Velocity boundary layer[5]

Conservation of mass equation

The principle of conservation of mass is that mass cannot be either created or destroyed and in analysis process all the mass must be accounted in steady flow, in a control volume the amount of mass remains constant and it is expressed as

Rate of mass flow into the control volume = rate of mass flow out of the volume control

$$\frac{du}{dx} + \frac{dv}{dy} = 0 \qquad (4)$$

This equation is conservation of mass equation relation. Also called continuity equation or mass balance for two dimensional steady state flow.

Conservation of momentum equation

Second law of newton is the expression for conservation of momentum it states that, the total force acting on controlled volume is equal to the product of mass to the acceleration of the fluid particles within the volume, is also equal to the conservation of momentum equation.

[Mass * Acceleration in specific direction.] = [Total force of the body.]

$$p\left(u\frac{du}{dx}+v\frac{dv}{dy}\right)=\ \mu\frac{d^2u}{dy^2}-\frac{dp}{dx} \qquad (5)$$

This relation is called conservation of momentum equation, in x axis of momentum equation.

Conservation of energy equation

Any undergoing process in a system is expressed as $E_{in} - E_{out} = \Delta E_{system}$. Which states that the change in energy content of system during a process is equal to difference between the input and output energy. The total energy content of control volume during the steady state flow remains constant. In a control volume the amount of energy entering in all forms must be equal to the amount of energy leaving it. The general equation for steady flow process is

$$\dot{E}in-\ \dot{E}out=0 \qquad (6)$$

Forced Convection

The convection occurs due to motion of fluid over the surface by some external factors like fan or pump. This motion of fluid again classified based on internal and external flow. In the external flow the frequently occurring practice is drag force and friction, these two phenomena are physically describing it. The velocity of fluid exerts tangential shear force on the surface. In the internal flow of fluid, mostly liquids flowing in circular pipes which withstand high pressure difference between inside and outside of it. The flow maybe either laminar or turbulent flow which can be figured by some dimensionless number ranging's.[6]

Natural Convection

The convection takes place where the velocity of fluid is zero i.e., the motion of fluid around an object is stationary and it forms a thermal boundary layer of warmer air which interacts with the outer layer and heat transfer takes place. This is physical phenomena is normally occurring most of the practical situations like in refrigeration coils, in TV's etc. This natural convection flow can occur in both internal and external forms. And characteristic of flow can be laminar or turbulent flow.

The complex forms variables are used to determine the convection heat transfer. Since to make it simple terms dimensionless number are used. It can also use to find the heat transfer co-efficient.[7]

2.4 RADIATION

Electromagnetic waves which are emitted due to heat transfer is called thermal radiation. The magnitude of radiation emitted in a space is radiation intensity. There are some radiative properties of materials will be discussed such as emissivity, absorptivity, reflectivity, and transmissivity which are dependent on wavelength, temperature, direction.[8]

Basic Concepts

Some basic radiative properties, thermal properties of Radiation are seen.

Plank's constant

Max Planck in his quantum theory proposed that, a propagation of collective package of discrete energy is called as photons. The energy of photons is inversely proportional to its wavelength.

$$e = \frac{hc}{\lambda} \tag{7}$$

Where,

h = $6.6256*10^{-34}$ J is Planck's constant.

Blackbody Radiation

A body which absorbs all the incident radiation and also emits radiation in all direction is called Blackbody. Since it emits radiation in all direction it is also called diffuse emitter. Joseph Stefan experimentally figured the energy of radiation emitted by the blackbody for per unit time and per unit surface is expressed as

$$E_b = \sigma T^4 \, [\mathrm{W}/m^2] \tag{8}$$

Where,

$\sigma = 5.67*10^{-8}$ W/m^2. K^4 is Stefan Boltzmann constant. It is also known as blackbody emissive power.

T- temperature K

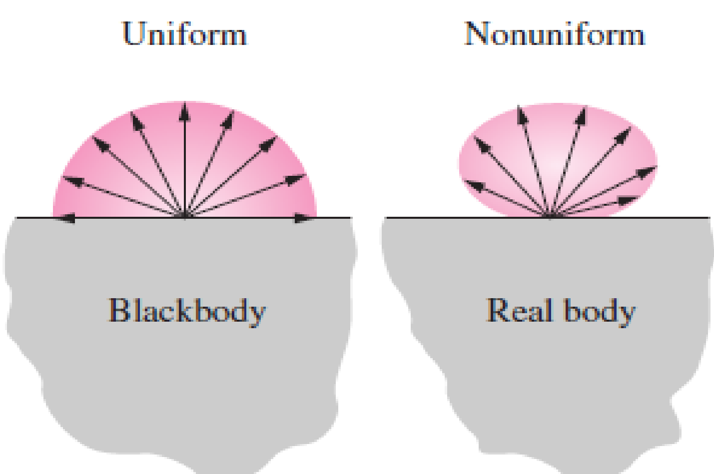

Figure 4: Difference in blackbody surface and real surface.[8]

This above law gives the net blackbody emissive power E_b, which is sum of the wavelength of overall emitted radiation. Thus we need to know the spectral blackbody radiation, states that amount of emitted radiation energy by a blackbody at an absolute temperature T for per unit time, surface area and wavelength about wavelength.

In 1901 max plank developed a relation for spectral blackbody radiation, it is expressed as,

$$E_{b\lambda} = \frac{C1}{\lambda^5\left[\exp\left(\frac{C2}{\lambda T}\right)-1\right]} \quad [\mathrm{W}/m^2\,.\,\mu\mathrm{m}] \tag{9}$$

Where,

$C1 = 2\pi\, hc_0^2 = 3.742E8\ \mu m^4/m^2$

$C2 = hc_0/k = 1.439E4\ \mu m.\ K$

In this k = 1.38065E-23 J/K is Boltzmann's constant.

T is Temperature in kelvins.

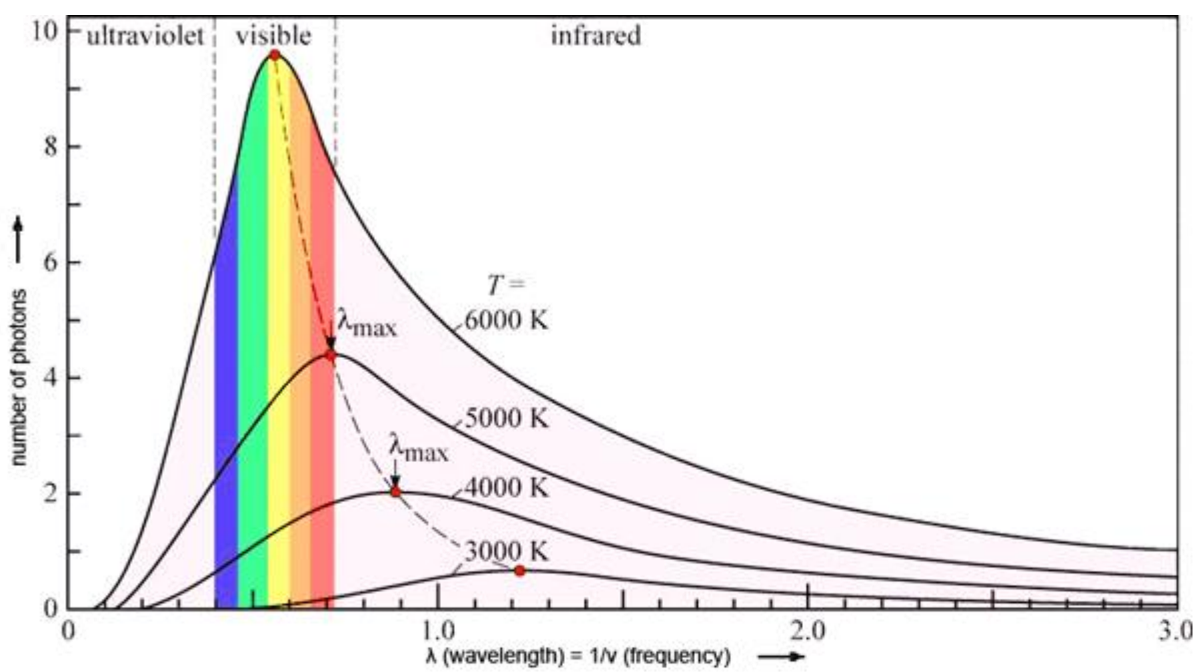

Figure 5: The variation of emissive power of blackbody with wavelength for several temperatures.[9]

From the above figure several observations has been made,

1.Wavelength is the continues function of emitted radiation. Temperature at any specific point the wavelength increases and reaches a peak and then temperature decreases with increase in wavelength.

2.radaition emitted at any wavelength increases with increase in temperature.

3.curve shift to left to shorter wavelength region as the temperature increase.

4. sun emits radiation and it is considered as blackbody at 5780 K and in the visible spectrum region as it reaches to its peak.

A Wien's displacement law gives the specific temperature at which the peak wavelength occurs.

$$(\lambda T)_{max\ power} = 2897.8 \quad [\mu m.\ K] \tag{10}$$

Radiosity

It is defined as the rate at which the energy of radiation leaves a surface of unit area in all direction is radiosity. It is expressed as J.

Emissivity

It is defined as the ratio of emitted surface radiation at a given temperature to the emitted radiation emitted by blackbody at the same temperature. It is expressed as ε. The emissivity different surface behaves differently, however for the blackbody the emissivity is 1. Hence the emissivity of real surface is not constant. It depends on the respective wavelength and temperature.

Absorptivity

It is defined as the ratio of radiation absorbed by the surface to the radiation incident on the surface. It is denoted by α.

$$\text{Absorptivity } \alpha = \frac{Absorbed\ radiation}{Incident\ radiation} = \frac{Gabs}{G} \tag{11}$$

Reflectivity

It is the ratio of radiation reflected from the surface to the incident radiation on the surface. It is denoted by ρ

$$\text{Reflectivity } \rho = \frac{Absorbed\ radiation}{Incident\ radiation} = \frac{Gref}{G} \quad (12)$$

Transmissivity

It is the ratio of the radiation transmitted through the surface to the incident radiation. It is denoted by τ

$$\text{Transmissivity } \tau = \frac{Absorbed\ radiation}{Incident\ radiation} = \frac{Gtr}{G} \quad (13)$$

Kirchhoff's law

It defined as the; at a given temperature the total emissivity of a surface is equal to the total absorptivity for radiation coming from it in the same temperature.

$$\varepsilon(T_\lambda) = \alpha\ (T_\lambda) \quad (14)$$

View Factor

A parameter which is used to define the radiation orientation effects between the surfaces while heat transfers is named as view factor. It is also called as configuration factor, shape factor, angle factor. In others words, considering two surfaces i and j thus the radiation between this is fraction of radiation leaving the surface i to the other surface j is said as view factor. It is denoted by F$i \rightarrow j$

Reciprocity Relation

It is a view factor relation between relative orientation and distance of two surfaces depends. It is valid unless the area A1 and A2 of two surface are equal.

It can be expressed as,

$$A_1\ F_{12} = A_2\ F_{21} \quad (15)$$

In some cases, the radiation leaving a surface i which strikes itself directly. It is named as F_{ii}. This occurs in curved or circular surfaces.

Summation Rule

The sum of the view factors from enclosed surface i to the all other enclosed surfaces including itself must be 1(unity).

$$\sum_{j=1}^{n} Fij = 1 \qquad (16)$$

In the cases of three surfaces, it is expressed as,

$$F_{11} + F_{12} + F_{13} = 1. \qquad (17)$$

2.5 DIMENSIONLESS NUMBERS

Reynolds Number: it is the ratio of inertial force to the viscous force.

$$Re = \frac{cL}{\upsilon} \qquad (18)$$

Where,

c - Fluid velocity m/s

L – Characteristic dimension m

υ - Kinematic viscosity m^2 /s

Grashof number: it is the ratio of buoyancy force and viscous force.

$$Gr = \frac{g\beta(T1-T2)Lc^3}{\upsilon\hat{}3} \qquad (19)$$

Where,

g= 9.81 Gravitational constant (m/s^2)

β- Co-efficient of volume of expansion (1/K)

(T1-T2) = Td, Temperature difference (K)

Lc - Thickness (m)

υ- Kinematic viscosity of fluid m^2/s

Prantl Number: it is the ratio of momentum of molecular diffusivity to the molecular diffusivity of heat.

$$Pr = \frac{\upsilon.\rho.Cp}{k} \tag{20}$$

Where,

υ- Kinematic viscosity of fluid m^2/s

ρ- Density kg/m^3

Cp- Specific heat capacity J/ Kg. K

k- Thermal conductivity $W/m^2.C$

Nusselt number: it is the ratio of convection by conduction of wall in which the boundary layer is related to boundary condition.

$$Nu = \frac{hL}{k} \tag{21}$$

Where,

h- Heat transfer co-efficient for convection $W/m^2.C$

L- Thickness m

k- Thermal Conductivity $W/m^2.C$

Rayleigh Number: it is the product of Grashof number to the Prantl number.

$$Ra = Gr.Pr \tag{22}$$

Biot Number: it is the ratio of convection and conduction.

$$Bi = \frac{hL}{k_w} \tag{23}$$

Where,

h- Heat transfer co-efficient for convection W/m^2.C

L- Thickness m

k- Thermal Conductivity of the wall W/m^2.C

Fourier Number: it is the ratio of characteristic dimension to the depth of the wave temperature.

$$Fo = \frac{\alpha t}{L^2} \tag{24}$$

Where,

α- Thermal Diffusivity m^2/s

t - Time s

L- Length m [1].

Chapter – 3

3.1 NATURAL CONVECTION INSIDE ENCLOSURES

In residents, heat loss occurs through the windows. Hence we insulate windows to prevent the loss of energy. Normal resident buildings are installed with transparent windows therefore heat loss occurs through it in more significant manner. Hence to reduce the heat loss and also need of transparent behavior; we use air as an insulating layer. Air is a good insulator. Based on some examination on thermal conductivities of insulating materials which reveals that air is good insulator and transparent. In order to use air as an insulator it should be covered in both side. hence the result of enclosed area called double pane window.

In general, the fluid in the enclosure are not stationary and heat transfer through the enclosure is complicated. In vertical enclosures, the region adjacent to the hotter surface the fluid temperature rises and adjacent to the cooler plate the temperature falls.

Normally heat transfer in an enclosure takes place when the hotter plate is either in the top or in the bottom. When the hotter plate is in the top, thus the heat transfer occurs due to the lighter fluid on the top and heavier fluid in the bottom and it is done by pure conduction. While, when bottom plate is hot then the heat transfers from heavier fluid to lighter fluid topple up the heavier fluid to rise to the top. Until then the transfer is conduction and then tendency of buoyancy force overcomes the fluid resistance and initiates natural convection.

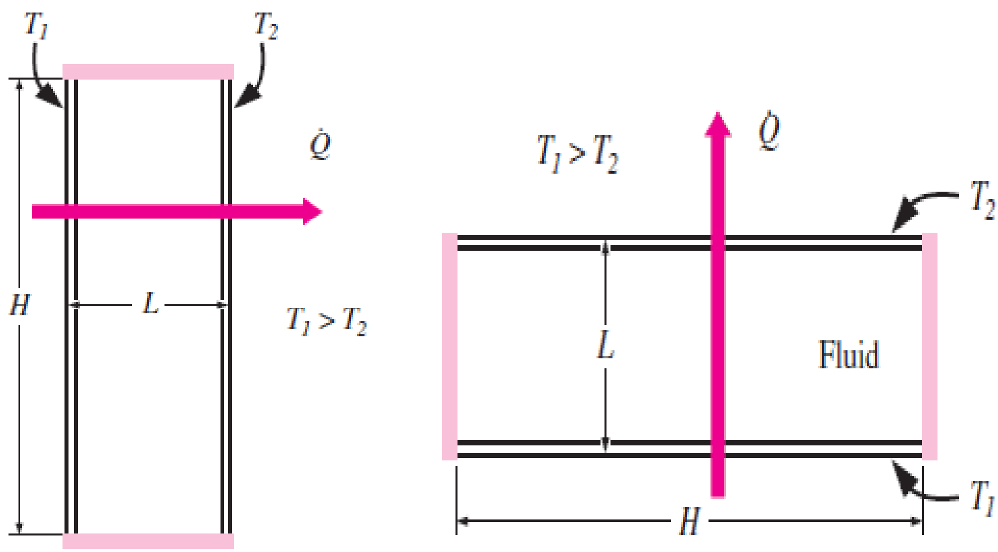

Figure 6: Vertical enclosure & horizontal enclosure.[7]

3.2 HEAT TRANSFER IN HORIZONTAL ENCLOSURE

In the horizontal enclosure, the convection takes place when the bottom plate is hot. Thus the convection currents flow through it and characteristics variables such as nusselt number and heat transfer co efficient. Convection does not occur when the upper plate is hot because of heat transfer through pure conduction.

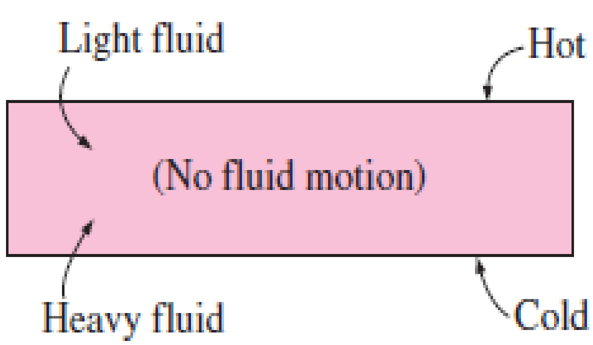

Figure 7: No convection.

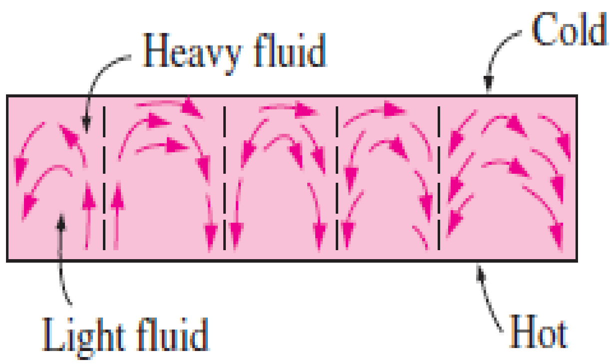

Figure 8: Convection currents.[7]

The fluid in the enclosed area behaves like a thermal conductivity fluid whose result of convection currents is kNu. This phenomenon is called effective thermal conductivity.

$$k_{eff} = \text{kNu.} \tag{25}$$

As said before, convection does not occur in a enclosure when the upper plate is hot i.e., Nu =1. Hence the lower plate with the higher temperature as significant enough for Rayleigh number to be the value of Ra > 1708.

Simple correlations for horizontal enclosures are,

$$Nu = 0.195\, Ra^{1/4} \qquad 10^4 < Ra < 4*10^5 \tag{26}$$

$$Nu = 0.068\, Ra^{1/3} \qquad 4*10^5 < Ra < 10^7 \tag{27}$$

Hollands et al experimentally recommend the co relation for horizontal enclosures of air which is expressed as,

$$Nu = 1 + 1.44\left(1 - \frac{1708}{Ra}\right)^{+} + \left(\frac{Ra^{\frac{1}{3}}}{18} - 1\right)^{+} \quad Ra < 10^8 \tag{28}$$

The notation [] $^+$, which indicates when the value in the bracket is negative then the then value should consider as zero.

Based upon this factors an experiment is done, which will be briefly described.

3.3 EXPERIMENTAL DETERMINATION OF CRITERIAL EQUATION FOR NUSSELT NUMBER AND FINDING CONSTANTS OF C AND N

The experiment is conducted on instrument called HFM 436 Lambda (Heat Flow Meters), it is a measuring instrument used to measure the thermal conductivity of the materials. With the help of this instrument the values of heat flux and other significant values are able to be calculated.

HFM 436/3/1E Lambda

Heat flow meter are used to measure the thermal conductivity of the materials which have low conductivity such as insulation materials. This instrument is very accurate as it is calibrated on test according to ASTM method C518, ISO 8301, JIS A1412 and DIN EN 12667. It has speed of measurement and precision to patented temperature control and heat flus measurement technology. The outcome of the results will be excellent accuracy and repeatability.

Features of HFM 436/3/1E Lambda

Plate temperature control is patented (US- patent No. 5940784)

- Easy and fast to use.
- Operation is semi-automated.
- Quick launch testing setup
- Stable, Accurate, precise.

There are variety of range of instruments manufactured by NETZSCH. In this case, HFM 436/3/1E Lambda is used. Since as the material used in it is expanded polystyrene(EPS). EPS is very rigid and closed packed structure hence acts as a good insulator.

Construction

The construction of the whole setup is basically simple. It consists of HFM 436 Lambda, Computer, Cooling system, Printer. The instrument is connected with computer to display the values of thermal conductivity and other related values like upper plate temperature, lower plate temperature, mean temperature, temperature difference and so on. And in the same manner a cooling system and printer is also connected to the instrument. The cooling system is used to maintain the temperature of both the upper and lower plates. The printer is used to print the values for future purpose. There are two ways to use the instrument one is by itself with controls in the machine which is usually done in trained technician or in industries for frequent testing purpose. Another method is by using Q-LAB software which is more easy way of handling the instrument and the values can be seen time to time when it is processing.

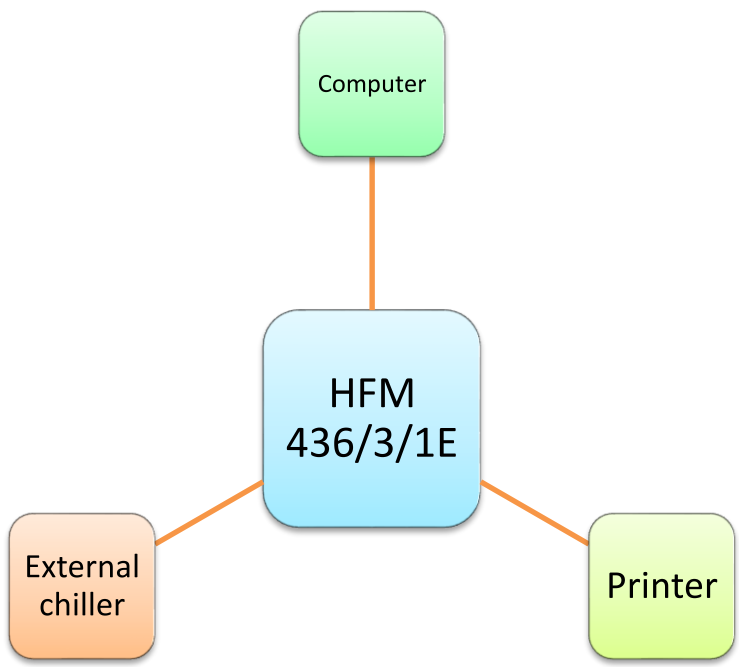

Figure 9: Schematic diagram of Experimental setup. Source [own]

Principle of operation

General Working Principle, usually a sample of material with thickness L is kept between the plates. Then the temperature of the plates is given as per the user. The temperature of the plates is controlled by the Peltier system, which is done using an integral fluid circle. This fluid is then cooled by External chiller. Thermocouple is placed in the plates which is used to measure the temperature drop across material. Heat flux transducers are mounted on each plate. These transducers measure the plate's voltage proportional to the flow of heat. Heat flux transducer and the thermocouple reading indicate thermal equilibrium.

The usage of this instrument is slightly modified for the experimentation as such heat transfer between two plates to take place. There are 7 series of boards expanded polystyrene with thickness of approximately 1 cm each has been taken. Thus 7 readings taken by increasing the thickness i.e. by adding one more expanded polystyrene. The expanded polystyrene is cut middle in shape of square with the area of 0.102m, which is the actually area of the heat flux transducer in both plates. Thus this forms an enclosed area with both up and down sides covered by plates and right and left sides are covered by expanded polystyrene. Hence the temperature between two plates are assigned manually and heat transfer takes place in the enclosed area.

The instrument consists various parts which is shown below,

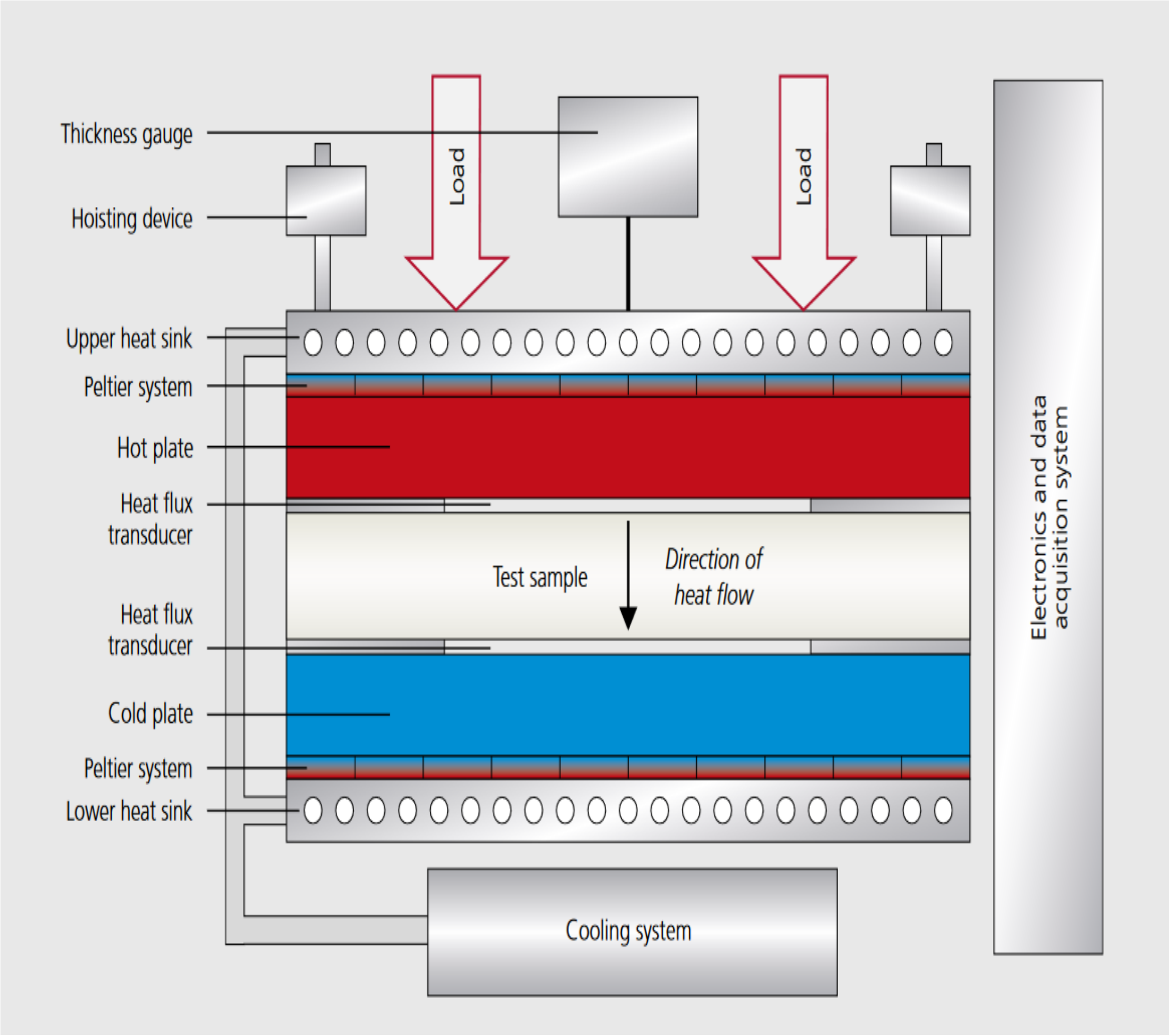

Figure: 10 Schematic design of HFM 436/3/1E.[10]

Q-lab Software

This software gives an enhanced flexibility in data handling, storage, instrument monitoring, programming. This software displays the readings of sample for over a time period until it reaches the equilibrium point. As it displays the values and stored. The features of this software is easy input, storage, calibration files can be restored, monitoring all the temperature and conductivity results.[10]

Specifications of the HFM

Table 1: Specification of HFM 436/3/1E.[10]

Context	**HFM 436/3/1 lambda**
Plate Temperature range	Variable 0 to 100 degree
Cooling system	Forced air
Plate temperature control	Peltier system
Programmable data points	10
Specimen size	300*300*100 mm^3
Thermal resistance range	0.1 to 0.8 m^2.K/W
Thermal conductivity	0.005 to 0.50 W/Mk
Repeatability	0.5 %
Accuracy	± 1 TO 3%
Dimensions (L*W*H)	48*63*51 cm^3

Chapter – 4

4.1 EXPERIMENTAL VALUES

For the measurement, two experimental setup has to be made. In the 1st setup higher temperature will be in the top. And in the 2nd higher temperature will be in bottom plate. In each setup, the measurement of values of seven boards of EPS (Expanded Polystyrene) has been inserted in the device, whenever one set attains the equilibrium and then next set is inserted. And experiment proceeds for the next setup and readings are taken as listed.

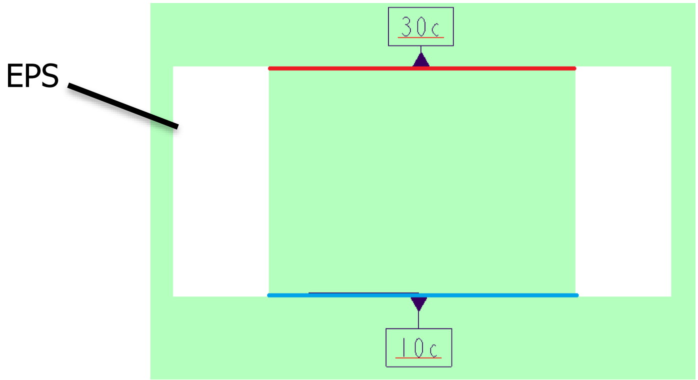

Figure 11: Experimental setup diagram for upper plate hot

Table 2: Experimental values of upper plate with higher temperature

Sample	Thickness of Air Layer	Upper Plate Temperature	Lower Plate Temperature	Mean Temperature
	m	° C	° C	° C
S1	0.011415	29.45	9.49	19.47
S2	0.022733	30.23	9.80	20.02
S3	0.033898	30.40	9.72	20.06
S4	0.045399	30.50	9.68	20.09
S5	0.057011	30.56	9.59	20.07
S6	0.068083	29.92	9.70	19.81
S7	0.079238	29.65	9.65	19.80

Table 3 Experimental values of upper plate with higher temperature

Delta Temperature	Thermal Conductivity	Thermal Resistance
° C	**W/ m² k**	**m² k/W**
19.96	0.073289	0.155758
20.44	0.118195	0.192334
20.69	0.159128	0.213025
20.82	0.196551	0.230978
20.97	0.228641	0.249349
20.22	0.253560	0.268508
20.29	0.278769	0.284241

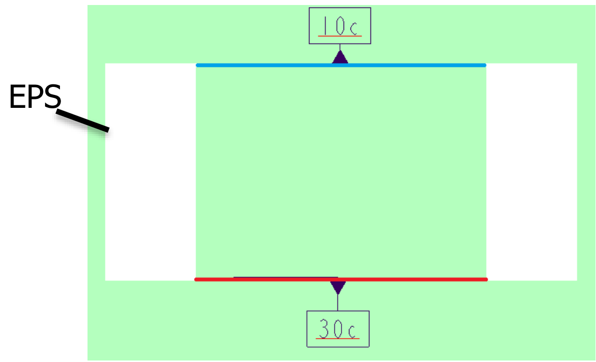

Figure 12: Experimental setup diagram for lower plate hot. Source [own]

Table 4: Experimental values of lower plate with higher temperature

Sample	Thickness of Air Layer	Upper Plate Temperature	Lower Plate Temperature	Mean Temperature
	m	° C	° C	° C
S1	0.011375	9.49	29.45	20.59
S2	0.022740	9.80	30.23	20.04
S3	0.033900	9.72	30.40	20.30
S4	0.045363	9.68	30.50	20.60
S5	0.057000	9.59	30.56	20.57
S6	0.068085	9.70	29.92	20.67
S7	0.079249	9.65	29.65	20.61

Table 5: Experimental values of lower plate with higher temperature

Delta Temperature	Thermal Conductivity	Thermal Resistance
° C	W/ m^2 k	m^2 k/W
19.24	0.083193	0.136736
19.34	0.163803	0.138827
19.62	0.227487	0.149018
19.83	0.289858	0.149018
20.01	0.346899	0.156501
20.14	0.399625	0.164314
20.12	0.449708	0.176223

Above are experimental readings from the device which displayed in Q lab software. And this values used for the determination of criterial equation.

4.2 CALCULATION

For the calculation of criterial equation of Nusselt number of c & n constants

This calculation is for one set of values and for the other set of values the final values are listed in tables,

$$Nu = cRa^n \tag{29}$$

$$Ra = Gr.Pr \tag{30}$$

$$Gr = \frac{g\beta(T1-T2)Lc^3}{\upsilon\hat{}3} \tag{31}$$

Gr- Grashof number

g= 9.81 gravitational constant (m/s^2)

β- co-efficient of volume of expansion (1/K)

$$\frac{1}{(273+\mathrm{Tm})} = \frac{1}{273+19.93} = 0.00314\ \mathrm{K}^{-1}$$

Where Tm is Mean temperature.

(T1-T2) = Td, temperature difference (delta temperature)1 (K)

Lc- thickness (m)

υ- kinematic viscosity of fluid m^2/s (in this case AIR)

Pr = 0.715, From the tables.[11]

The above value is approximately equal to the value of Prantl number. At atmospheric pressure.

A-Area of the transducer

A = 0.102^2 =0.0104 m^2

This area is the measuring area and also for the square hole area of the expanded polystyrene. By this way the flux voltage is produced and converted in to values. And displayed in the monitor.

Steps involve in finding constants

$$Gr = \frac{9.81 * 0.0314 * 19.24 * (0.01138^3)}{(1.5116\text{e} - 6)2}$$

Gr= 4134.88

Ra= 4134.88*0.715

Ra= 2956.167

Nusselt number is figured by calculating the values of heat transferred by conduction and radiation as shown below,

$$\dot{Q} = \frac{\text{k}*\text{A}*\text{Td}}{L} \quad \text{W} \tag{32}$$

$\dot{Q}$- Heat flux (W)

k- Thermal Conductivity W/m^{2}K

k=0.0231, the value of thermal conductivity is determined by linear graphical method of the experimental values. This can be explained by the following terms,

$$Qts = ks * dt * L \qquad \text{W/m}^2 \tag{33}$$

$$Qts = Q_{cond} + Q_{rad} \tag{34}$$

Where,

Qts – Heat transfer through the system.

Q_{Cond} – Heat transfer through conduction.

Q_{rad} – Heat transfer through radiation.

$$ks.dt.L = [k.dt.L] + \text{Qrad} \tag{35}$$

$$ks = k + \frac{[(\text{Qrad}) * L]}{dt\ .A} \tag{36}$$

Thus from the above equation, when the thickness L trends to zero the value of will be Ks= k = 0.0231 W/m^2. K.

Heat flux by conduction,

$$\dot{Q}_{cond} = \frac{\text{k}*\text{A}*\text{Td}}{L} \quad [\text{W}] \tag{37}$$

$$\dot{Q}_{cond} = \frac{0.0231*19.96*0.0104}{0.01142} \quad [\text{W}]$$

$$\dot{Q}_{cond} = 0.42024\ [W]$$

Total Heat flux transferred is,

$$\dot{Q}_{tot}\ conduction_{\text{t}} = \dot{Q}_{cond} + \dot{Q}_{rad} \tag{38}$$

$$\dot{Q}_{tot} = \frac{\text{Td} * \text{A}}{\text{R}}$$

$$\dot{Q}_{tot} = \frac{19.96 * 0.0104}{0.15576}$$

$$\dot{Q}_{tot} = 1.33325\ [W]$$

$$\dot{Q}_{rad} = \dot{Q}_{tot} - \dot{Q}_{cond} \tag{39}$$

$$= 1.33325 - 0.42024$$

$$\dot{Q}_{rad} = 0.91301\ [W]$$

***Above values are taken from the readings where the condition of temperature of upper plate is higher.**

Now, since as spoken in convection for upcoming calculation the values of the temperature of lower plate is higher.

Heat flux through convection,

$$\dot{Q}_{tot} = \dot{Q}_{conv} + \dot{Q}_{rad} \tag{40}$$

$$\dot{Q}_{tot} = \frac{\mathrm{Td} * \mathrm{A}}{\mathrm{R}} \tag{41}$$

$$\dot{Q}_{tot} = \frac{19.24 * 0.0104}{0.13674}$$

$$\dot{Q}_{tot} = 1.46394\ W$$

$$\dot{Q}_{conv} = \dot{Q}_{tot} - \dot{Q}_{rad} \tag{42}$$

Heat Flux through convection is,

$$\dot{Q}_{conv} = 0.55093\ [W]$$

By newton's law of cooling'

$$\dot{Q} = \frac{\mathrm{k} * \mathrm{Nu} * \mathrm{A} * \mathrm{Td}}{\mathrm{L}} \tag{43}$$

$$Nu = \frac{\mathrm{Q} * \mathrm{L}}{(\mathrm{A} * \mathrm{Td} * \mathrm{k})} \tag{44}$$

Nu = 1.35529

$$Nu = cRa^{n}$$

By taking log on both sides'

$$\log Nu = log\ c + n \log Ra$$

Log 1.35529 = log c + n log2956.167

By using linear fit graph method, the values of above equation,

C= 0.123

N=0.302

Hence the experimentally determined criterial equation for Nusselt number is

$$Nu = 0.123\ Ra^{0.302} \tag{45}$$

This equation is calculated using the all the seven set of values of both the setup's.

By Hollands equation we can compare the Nusselt number values with the below equation,

$$Nu = 1 + 1.44\left(1 - \frac{1708}{Ra}\right)^{+} + \left(\frac{Ra^{\frac{1}{3}}}{18} - 1\right)^{+} \quad Ra < 10^{8} \tag{46}$$

Nu = 1.608

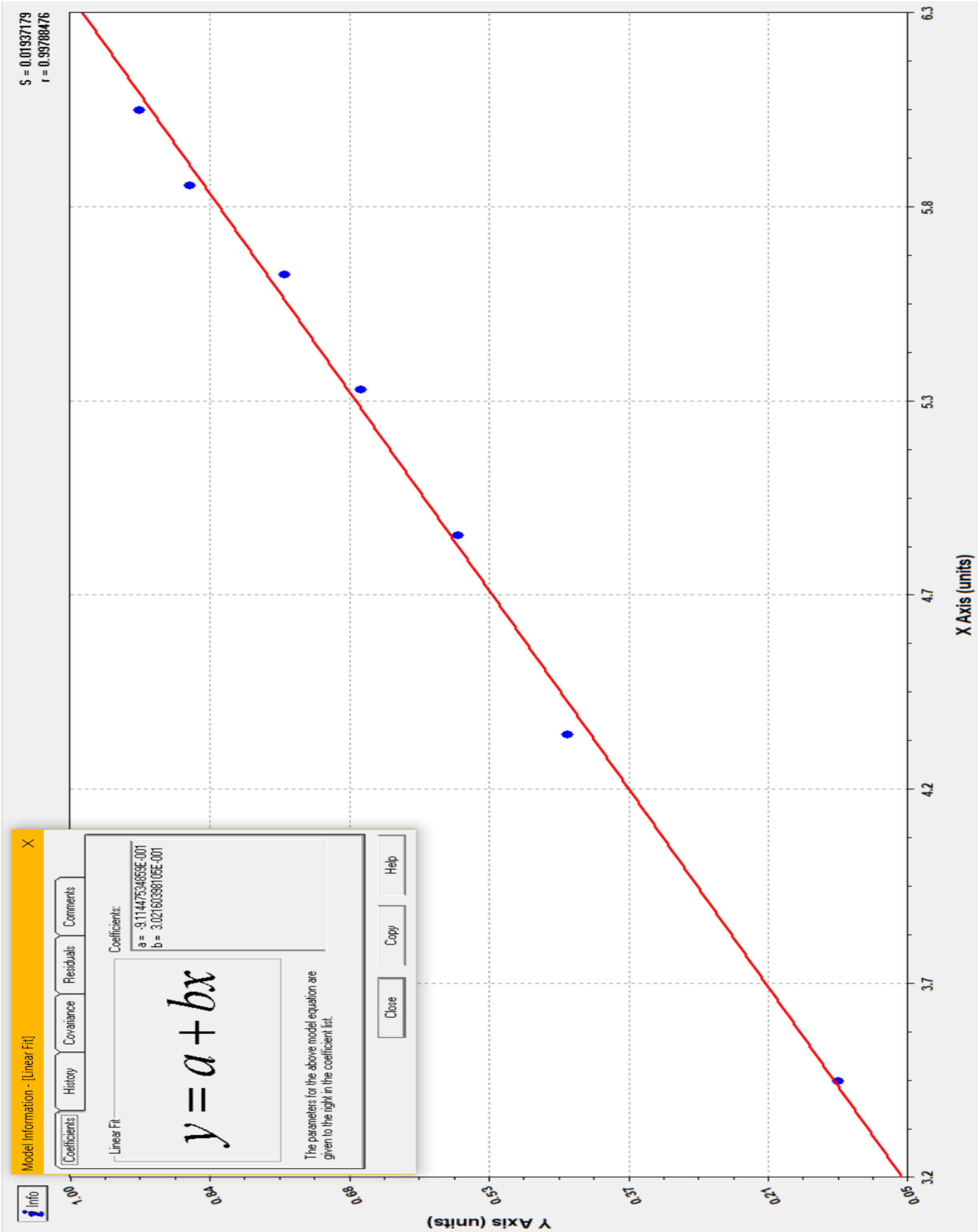

Figure 13: Linear graphical values for c&n. source [own]

Table 6: Calculated values from the experiment

Conduction	Conduction+ radiation	radiation	Convection+ radiation	convection	Co-eff of vol exp
$\dot{Q}_{cond}$	$\dot{Q}_{tot}$	$\dot{Q}_{rad}$	$\dot{Q}_{tot}$	$\dot{Q}_{conv}$	β
W	W	W	W	W	K^{-4}
0.42024	1.33325	0.91301	1.46394	0.55093	0.00341
0.216091	1.105669	0.889578	1.449382	0.559804	0.003411
0.146689	1.010486	0.863797	1.369811	0.506014	0.003408
0.110217	0.9378	0.827584	1.318275	0.490691	0.003404
0.0884	0.874966	0.786566	1.266989	0.480423	0.003405
0.071376	0.783473	0.712097	1.22987	0.517773	0.003403
0.06154	0.74267	0.681129	1.187861	0.506732	0.003404

Table 7: Calculated values from the experiment

Nusselt number	Nusselt number from Holland equation	Rayleigh Number
1.35529	1.608	2956.167
2.73878	2.93853	23943.910
3.6379	3.804465	80152.314
4.67062	4.63899	193210.487
5.69429	5.48207	386968.588
7.28314	7.17998	662745.376
8.30485	8.27544	1045068.86

In the above calculation the values of heat transfer by radiation are determined by experimental values. Now we are going to compare the values the of experimental values with analytically determining values.

Calculation of heat transfer through radiation using analytical method

This analytical method consists of various parameters to find the heat transmitted by radiation.

View factor

The fraction of radiation leaving the surface i and directly strikes the surface j.[12]

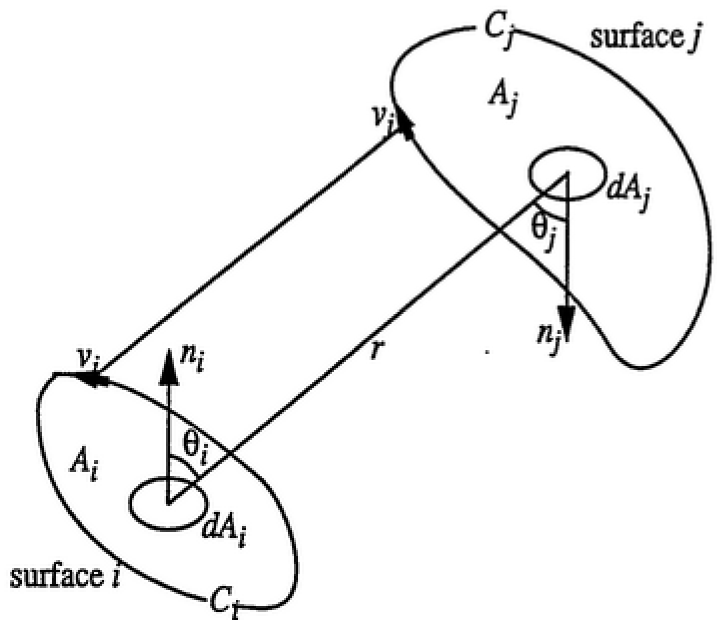

Figure 14: View factor.[13]

The view factor rectangular surface is,

$$F_{ij} = \frac{2}{\pi \bar{X}\bar{Y}}\left[ln\left(\frac{(1+\bar{X}^2)(1+\bar{Y}^2)}{1+\bar{X}^2+\bar{Y}^2}\right)^{\frac{1}{2}} + \bar{X}(1+\bar{Y}^2)^{\frac{1}{2}} + tan^{-1}\left(\frac{\bar{X}}{(1+\bar{Y}^2)^{\frac{1}{2}}}\right) + \bar{Y}(1+\bar{X}^2)^{\frac{1}{2}}\ tan^{-1}\left(\frac{\bar{Y}}{(1+\bar{X}^2)^{\frac{1}{2}}}\right) - \bar{X}\tan^{-1}\bar{X} - \bar{Y}\tan^{-1}\bar{Y}\right] \quad (47)$$

$$\bar{X} = \frac{X}{L}; \quad \bar{Y} = \frac{Y}{L}$$

Where in this case X=Y=0.102m, hence $\bar{X}=\bar{Y}$

L is Thickness = 0.011415

$$\bar{X} = 8.935611$$

$$\bar{Y} = 8.935611$$

From the above figure the view factor will be for, $F1 \rightarrow 2$ & $F1 \rightarrow 3$

$$F1 \rightarrow 2 = 0.81$$

By summation rule,

$$F1 \rightarrow 1 + F1 \rightarrow 2 + F1 \rightarrow 3 = 1$$

$F1 \rightarrow 1$ it represents the radiation leaves from surface 1 strikes itself. But in this case $F1 \rightarrow 1 = 0$

$$F1 \rightarrow 3 = 0.19$$

Emissivity of the surface of the plate is ε = 0.93

Stefan Boltzmann constant σ = 5.67e-8 $W/m^2 . K^4$

Analytical method of calculating radiation

The radiation commonly assumed as diffuse, gray, opaque. The surface which is not transparent is called diffuse emitters and reflectors, their properties are independent of wavelength and each surface of isothermal enclosure. Uniform form radiation over the surface by incoming and outgoing radiation.

$$\dot{Q} = [radiation\ leaving\ entire\ surface\ i] - [\ radiation\ incident\ on\ enitre\ surface\ i] \tag{48}$$

From ohm law electrical analogy,

$$Q_i = \frac{E_{bi} - J_i}{R_i}\ [W] \tag{49}$$

$$R_i = \frac{1-\varepsilon_i}{A_i.\varepsilon_i} \quad (50)$$

Where, R_i is surface resistance. Some in numerous practical heat transfer encounters as an adiabatic wall and it well insulated and total heat transfer through it is zero. When the convection currents on the side of walls are negligible and when the steady state conditions reached, the surface lose its radiation energy and gains as much as it. And hence $\dot{Q}_i = 0$. Thus this situation is known as reradiating surfaces.[12]

$$J_i = E_{bi} = \sigma T_i^4. \ [\frac{W}{m^2}] \quad (51)$$

In this experiment, the side walls are adiabatic. It is well insulated. The reasons are as follows,

1. The thickness of the expanded polystyrene is relatively large compare.
2. The temperature in the middle and the end are same.

Hence the side walls do not transfer heat hence it forms a reradiating surfaces, the equation for three surface is as follows,

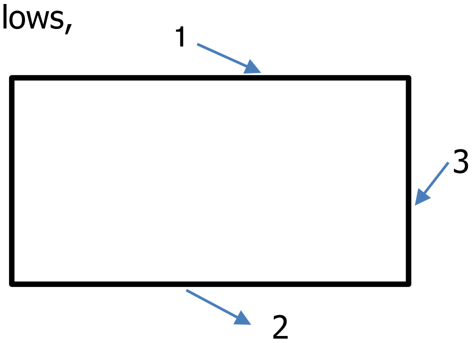

Figure 15: Three surface of view factor. Source [own]

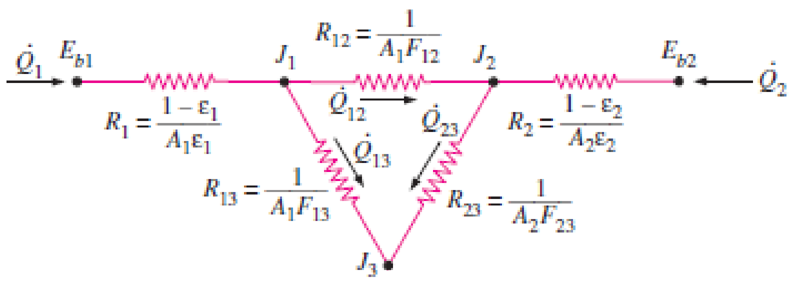

Figure 16: Three surface enclosure of radiation network.[12]

This above figure demonstrates the heat flux equation of three surface enclosure in which the equation can be defined as,

$$\dot{Q}_{re} = \frac{\sigma(Tu^4 - Tl^4)}{\frac{2*(1-\varepsilon)}{\varepsilon.A1} + \frac{1}{A1.F1\_2} + \frac{1}{\frac{2}{A1.F1\_3}}} \tag{52}$$

$$\dot{Q}_{re} = 0.946168\ W$$

This above values are calculated for only one set of values remaining values are listed in table.

Table 8: Analytical values of reemitted radiation.

$\overline{X}$	$\overline{Y}$	F1--2	F1--3	Q Re
-	-	-	-	W
8.935611	8.935611	0.81	0.19	0.946168
4.486869	4.486869	0.66	0.34	0.8782
3.009027	3.009027	0.55	0.45	0.824018
2.246746	2.246746	0.45	0.55	0.778798
1.789128	1.789128	0.38	0.62	0.741905
1.498171	1.498171	0.32	0.68	0.713324
1.287261	1.287261	0.27	0.73	0.689764

Chapter – 5

5.1 RESULTS AND DISCUSSIONS

The Criterial equation for applicability for Nusselt number is calculated experimentally as,

$$\boldsymbol{Nu = 0.123\ Ra^{0.302}}$$

The values of Nusselt number from experimental determined and from the Hollands equations are

Table 9: Experimental and hollands equation calculated nusselt umber

Experimental Calculated Nusselt Number	From Hollands Equation Nusselt Number
1.35529	1.608
2.73878	2.93853
3.6379	3.804465
4.67062	4.63899
5.69429	5.48207
7.28314	7.17998
8.30485	8.27544

The values of both Hollands equation and experimentally determined Nusselt number values are approximately equal and acceptable.

Analytical calculation of radiation is compared with the experimental value,

Table 10: Analytical vs Experimental calculated values

Analytical calculated Radiation	Experimentally calculated Radiation
$\dot{Q}$ [W]	**$\dot{Q}$ [W]**
0.946168	0.91301
0.8782	0.889578
0.824018	0.863797
0.778798	0.827584
0.741905	0.786566
0.713324	0.712097
0.689764	0.681129

The values analytical and experimental calculated values of radiation are approximately equal to each other.

5.2 CONCLUSION

The intention to find the criterial equation is found. The experimental work are compared with numerical and analytical methods and results are with better satisfaction. The flow of air in the enclosure is not constant due to the buoyancy effect. This leads to the natural convection mechanism to occur in the first place. In previous literatures the equation is expressed only in terms of analytical and numerical ways. The experimental result which is found also satisfying all the analytical conditions. The criterial equation for the Nusselt number is determined by using a measuring instrument HMF 436/3/1E Lambda which is used to measure the thermal conductivity of solid insulating material. This device has its own standard with accuracy of results. By setting up the experiment two sets of values of readings are obtained when each and every single time it attains an equilibrium point in the enclosure. Thus experimental values are calculated and compared with other numerical and analytical methods such as Hollands equation on N+usselt number and analytical method for radiation.

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