CHAPTER-I

INTRODUCTION

1.1 INTRODUCTION TO METAMATERIAL

Metamaterials are generally defined as artificially designed micro architectures with unusual physical properties that overcome the conventional limits of natural materials. The earliest studies on metamaterials have focused on the changes in optical or electromagnetic properties such as the negative refractive index. This concept of metamaterials was further extended to obtain unusual acoustic or mechanical properties. Mechanical metamaterials have employed micro scale architectures to enable unusual mechanical properties at the macro-scale, such as auxetic metamaterials with negative Poisson's ratio, Penta mode metamaterials with extremely low shear modulus, and dilatational metamaterials with extremely high shear modulus. In terms of thermal properties, micro architecture cellular structures have been used to realize negative thermal expansion. Other types of thermal metamaterial have been studied for enabling effective control of heat flux and increasing the thermal resistance of cellular structures. In terms of thermal resistance, high thermal resistance (i.e., low thermal conductivity) materials are used for thermal insulators in many engineering applications. Insulation materials have low thermal conductivity, generally of less than 0.1 W/m-K, and can be categorized as organic or inorganic materials. The most popular organic insulators are polymer-based foams such as polystyrene or polyurethane foam, and the most popular inorganic insulators are inorganic fibrous materials such as glass wool or stone wool. Although these foamy or fibrous materials have excellent thermal resistance, they are limited in their ability to be used as structural components because of their low rigidity and strength. Instead, ceramic materials have high rigidity and thermal resistance, and thus they have been used as thermal insulators in various types of furnaces and engines. However, ceramics are difficult-to-cut materials, and thus are not easy to shape into a complicated geometry.

Metal foams are cellular metals with a large volume of porosities, which reduces their thermal conductivity by more than 1/10.Metal foams are advantageous in their structural rigidity and energy absorption capability, allowing them to be used as thermal insulators under relatively high load or temperature conditions. Metal foams are usually manufactured by the powder metallurgy method, and thus their cell size and structure are not uniform nor controllable. In recent years, additive manufacturing (AM) has been used to design and fabricate uniform cellular structures. Whereas the relevant studies have mainly focused on investigating the structural efficiency of lattice structures, the thermal conductivity of additively manufactured lattice structures was also studied in terms of the effects of the lattice design and volume fraction. This study aims to develop a novel thermal metamaterial that provides high thermal resistance together with cooling capability, whereas a typical thermal insulator inherently has low cooling capability. For this purpose, we used a cellular lattice structure using a body-centered cubic (BCC) unit cell. A numerical scheme was developed to design a conformal cellular structure based on a hexahedral mesh of the target solid. Finite element (FE) analyses were conducted to investigate the thermal and structural responses of cellular cubes with variations in the lattice size. The selected lattice designs were then fabricated using AM, and heat conduction experiments were performed to evaluate the thermal resistance of the cellular cubes. Based on these studies, a thermal meta material was designed to act as a thermal insulator as well as a heat exchanger by enforcing coolant flow through the lattice structure. A test section was then prepared by installing the fabricated meta material between a flat heater and a cooling channel, and its thermal efficiency was investigated during a cycle of heating and cooling.

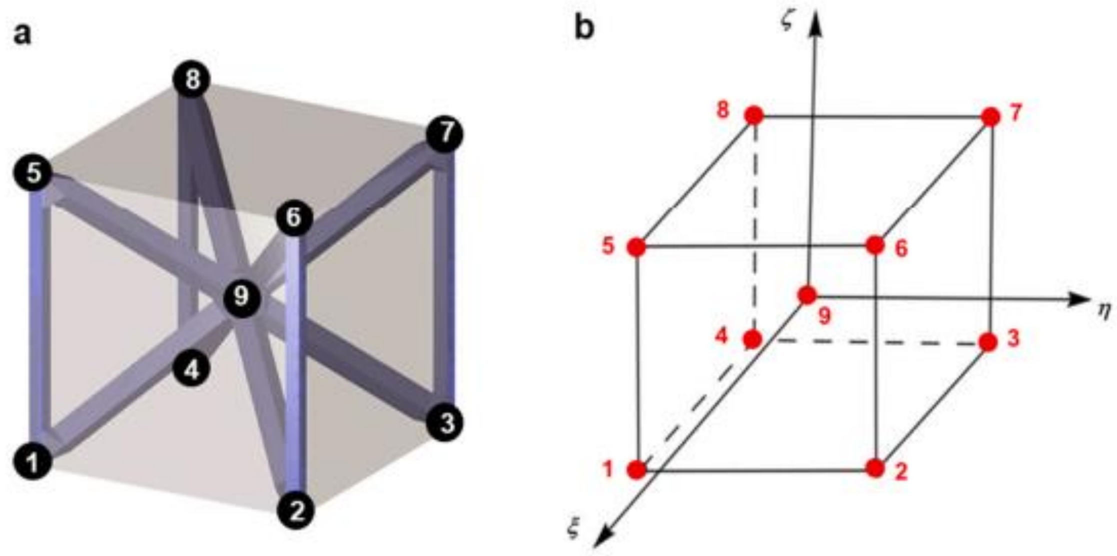

Fig 1.1 BCC Lattice Structure

1.2 HISTORY OF META MATERIALS

The history of metamaterials begins with artificial dielectrics in microwave engineering as it developed just after World War II. Yet, there are seminal explorations of artificial materials for manipulating electromagnetic waves at the end of the 19th century. Hence, the history of metamaterials is essentially a history of developing certain types of manufactured materials, which interact at radio frequency, microwave, and later optical frequencies.

As the science of materials has advanced, photonic materials have been developed which use the photon of light as the fundamental carrier of information. This has led to photonic crystals, and at the beginning of the new millennium, the proof of principle for functioning metamaterials with a negative index of refraction in the microwave- (at 10.5 Gigahertz) and optical range. This was followed by the first proof of principle for Meta material cloaking (shielding an object from view), also in the microwave range, about six years later. However, a cloak that can conceal objects across the entire electromagnetic spectrum is still decades away. Many physics and engineering problems need to be solved.

Nevertheless, negative refractive materials have led to the development of meta-Material antennas and meta material microwave lenses for miniature wireless system antennas which are more efficient than their conventional counterparts. Also, Meta material antennas are now commercially available. Meanwhile, sub wave length focusing with the super lens is also a part of present-day metamaterials research.

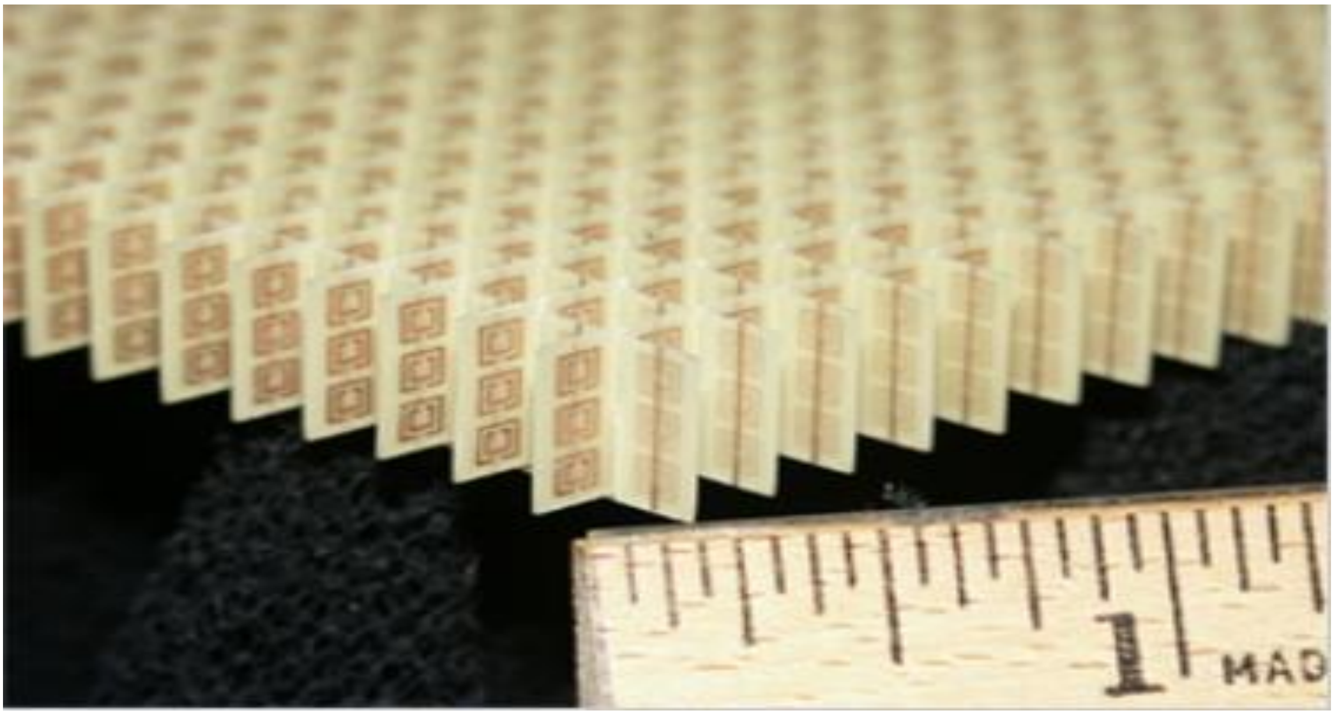

Fig 1.2 Optical Meta Material

CHAPTER-II

LITERATURE REVIEW

2.1 LITERATURE REVIEW

Thermally Materials are broadly are classified in to conductors and insulators a given material can be either conductor or insulator. conductor has capacity to conduct heat or to transfer heat, insulator has capacity for insulating. We have developed a Meta material by enhancing properties, which has capacity to conduct the heat and also act as partial insulator, which can insulate heat for some extent. since a property given to it thermally advantageous, named it as thermal meta materials. We have done this by taking reference from different research papers and articles that are published before, major contribution comes from the following papers.

CONTROLLING MACROSCOPIC HEAT TRANSFER WITH THERMAL METAMATERIALS: THEORY, EXPERIMENT AND APPLICATION

(PUBLISHED ON DECEMBER 2020)

AUTHORS:

- Shuai yang
- Jun wang

Classical thermodynamics often helps to passively describe macroscopic heat phenomena of natural systems, which means people almost cannot change the heat phenomena, but understand them according to the four thermodynamic laws. In contrast, thermal metamaterials, together with the governing theories, make it possible to actively manipulate macroscopic heat phenomena of artificial systems, which enables people to change the heat phenomena at will. Such metamaterials or metamaterial-based devices refer to those artificial structures that yield novel functions in controlling heat transfer. Since the concept of thermal cloak was proposed in 2008, this field has been developed rapidly with fruitful research results, which range from both theoretical models and experimental techniques in scientific research to practical applications in industry, such as radiative cooling and infrared camouflage. In this review, we comb through the research history of thermal metamaterials, and present novel functions and their associated theories in four areas. Such theories include both transformation theories and their extended theories, which are called theoretical thermotic for convenience. The four areas are classified according to the different ways of heat transfer, namely, heat conduction, heat conduction-convection, heat conduction-radiation, and heat conduction-convection-radiation. The corresponding experiments and applications are also introduced. At last, we provide our views on future opportunities and challenges in thermotic of metamaterials

A BRIEF REVIEW ON THERMAL METAMATERIALS FOR CLOAKING AND HEAT FLUX MANIPULATION

AUTHORS:

- Ignacio Peralta, V. Fachinotti, J. C. Álvarez Hostos
- Published 25 November 2019
- Materials Science
- Advanced Engineering Materials

Progress in material science has allowed the control of different physical fields in a manner that would be unachievable with ordinary materials. The development of engineered materials (the so-called metamaterials) to control the conductive heat flux has revolutionized the manner of manipulating thermal energy and allowed the possibility of guiding the heat flux in ways difficult to accept for human intuition. Herein, a brief review regarding the recent progress and developments in thermal metamaterials conceived to perform several conductive heat flux manipulation tasks is provided. Deeply theoretical discussions concerning design methodologies are left a side, and the focus is made on the design and manufacturing feasibility of metamaterials for thermal cloaking and camouflage, heat flux concentration, and inversion, among other applications that lead to the next generation of thermal devices.

DESIGN OF THERMAL METAMATERIALS WITH EXCELLENT THERMAL CONTROL FUNCTIONS BY USING FUNCTIONAL NANOPOROUS GRAPHENE

- Pin-Zhen Jia
- Published 10 August 2020
- Engineering, Physics, Materials Science
- physics status solidi (RRL) – Rapid Research Letters

Thermal metamaterials can effectively manipulate heat flux to achieve different thermal management functions, such as thermal cloak, concentrator, and rotator. To date, most of these metamaterials are based on macroscopic compound structures, such as metal/polymer. Herein, the concept of thermal metamaterials is extended to two-dimensional (2D) graphene-based systems because of their fast response speeds, in contrast to traditional three-dimensional metamaterials. Three thermal metamaterials with heterogeneous thermal parameters are constructed using nano-holed graphene, and some extraordinary thermal phenomena, such as effective shielding, accumulation and rotation of heat flux, are observed due to the significant anisotropic thermal conductivity of these 2D systems. Moreover, these thermal phenomena are insensitive to external disturbances. For designing thermal metamaterials, this study provides a novel approach, which can be applied to other 2D thermal functional materials.

CHAPTER-III

METHODOLGY

3.1 ADDITIVE MANUFACTURING

Additive manufacturing uses data computer-aided-design (CAD) software or 3D object scanners to direct hardware to deposit material, layer upon layer, in precise geometric shapes. As its name implies, additive manufacturing adds material to create an object. By contrast, when you create an object by traditional means, it is often necessary to remove material through milling, machining, carving, shaping or other means.

Although the terms "**3D printing"** and **"rapid prototyping"** are casually used to discuss additive manufacturing, each process is actually a subset of additive manufacturing.

There are seven main additive manufacturing technologies viz Vat photopolymerization, Material Extrusion, Material Jetting, Binder Jetting, Powder bed fusion, directed energy deposition, and Sheet lamination.

VAT PHOTOPOLYMERIZATION

This process uses a technique called Photopolymerization, in which radiation curable resins or photopolymers are used to create three-dimensional objects by selectively exposing them to ultraviolet light. When exposed, these materials undergo a chemical reaction and become solid. Only plastics can be printed using these technologies.

There are three main types under this category – Stereolithography, Digital Light Processing and Continuous Digital Light Processing.

BINDER JETTING PROCESS

As the name implies, Binder Jetting selectively deposits the bonding agent, a binding liquid, to join the powder material to form a 3D part. This process is different to any other AM technology as it does not employ heat during the process like others to fuse the material.

The print head and a powder spreader deposit alternating layers of bonding agent and build material to form a 3d object

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DIRECTED ENERGY DEPOSITION

Directed energy deposition technology uses focused thermal energy such as a laser, electron beam, or plasma arc to melt and fuse the material as they are deposited to create a 3d object. These are very similar to the welding process but very finely detailed.

The geometric information included in a Computer-Aided Design (CAD) solid model is used by LENS 3D printers to autonomously direct the DED process as it builds up a part layer by layer.

The two main types of Directed energy deposition technologies are LENS and EBAM. EBAM uses an electron beam, and LENS uses a focused laser to melt the material.

MATERIAL EXTRUSION

Material Extrusion is an additive manufacturing technique that uses a continuous filament of thermoplastic or composite material to construct 3D parts. Material extrusion was initially developed and patent by S. Scott Crump under Fused Deposition Modelling (FDM) in the 1980s.

In this additive manufacturing technique, the continuous filament of thermoplastic is fed through a heated nozzle before being deposited layer by layer onto the build platform to create the object.

MATERIAL JETTING

In material jetting, build material droplets are selectively deposited layer by layer into the build platform to form a 3D part.

This additive manufacturing technique is very similar to standard inkjet printers, where the material droplets are deposited layer by layer selectively to create a three-dimensional object. Once a layer is complete, its cured by ultraviolet light.

The powder material jetting includes the following commonly used printing technologies: UV cured Material Jetting, Drop on Demand (DOD), Nanoparticle Jetting (NPJ).

POWDER BED FUSION

Powder bed fusion is an Additive Manufacturing technique that uses either laser or electron beam to melt and fuse the material to form a 3D geometry part. The Powder Bed Fusion includes the following commonly used printing technologies: Multi Jet Fusion (MJF), Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS).

Powder bed fusion processes, especially selective laser sintering, are early industrial additive manufacturing techniques. This method uses a laser or electron beam to melt the powdered material and fuse them to create a solid object.

SHEET LAMINATION

Sheet lamination technologies use sheets of material to create 3D objects by stacking them and laminating them using either adhesive or ultrasonic welding. Once the object is built, the unwanted areas of the sections are removed layer by layer.

Sheet lamination technology is an umbrella term for Ultrasonic Additive Manufacturing (UAM, Selective Deposition Lamination (SDL, and Laminated Object Manufacturing (LOM).

3D MODEL CREATION STEP

First, the designer creates a 3D model of the object to be printed using computer-aided design (CAD) software or a 3D object scanner. Since the part is a replica of the 3D model, every detail needs to be correct and fully defined its external geometry.

Although AM can print complex parts and gives the product designer more design flexibility than conventional manufacturing processes, there are still limitations and rules to adhere to when designing to achieve the best results.

The design guides vary according to the additive manufacturing technology type and material selection. Equipment manufacturers and AM technology service providers have extensive design guides on designing parts. Refer to the types of AM technology and their manufacturers to find out more.

PLASTIC

Out of all the raw materials for 3D printing in use today, plastic is the most common. Plastic is one of the most diverse materials for 3D-printed toys and household fixtures. Products made with this technique include desk utensils, vases and action figures. Available in transparent form as well as bright colors — of which red and lime green are particularly popular — plastic filaments are sold on spools and can have either a matte or shiny texture.

With its firmness, flexibility, smoothness and bright range of color options, the appeal of plastic is easy to understand. As a relatively affordable option, plastic is generally light on the pocketbooks of creators and consumers alike.

Plastic products are generally made with FDM printers, in which thermoplastic filaments are melted and molded into shape, layer by layer. The types of plastic used in this process are usually made from one of the following materials:

- Polylactic acid (PLA)
- Acrylonitrile butadiene styrene (ABS)
- Polyvinyl Alcohol Plastic (PVA)
- Polycarbonate (PC)

Plastic items made in 3D printers come in a variety of shapes and consistencies, from flat and round to grooved and meshed. A quick search of Google images will show a novel range of 3D-printed plastic products such as mesh bracelets, cog wheels and Incredible Hulk action figures. For the home craftsperson, polycarbonate spools can now be purchased in bright colors at most supply stores.

-------our project material is based on **ABS,** so now discuss about that----

3.2 ACRYLONITRILE BUTADIENE STYRENE

Acrylonitrile butadiene styrene (ABS) (chemical formula $(C_8H_8)_x\cdot(C_4H_6)_y\cdot(C_3H_3N)_z$) is a common thermoplastic polymer. Its glass transition temperature is approximately 105 °C (221 °F). ABS is amorphous and therefore has no true melting point.

ABS is a terpolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The proportions can vary from 15% to 35% acrylonitrile, 5% to 30% butadiene and 40% to 60% styrene. The result is a long chain of polybutadiene crisscrossed with shorter chains of poly(styrene-co-acrylonitrile). The nitrile groups from neighboring chains, being polar, attract each other and bind the chains together, making ABS stronger than pure polystyrene. The acrylonitrile also contributes chemical resistance, fatigue resistance, hardness, and rigidity, while increasing the heat deflection temperature. The styrene gives the plastic a shiny, impervious surface, as well as hardness, rigidity, and improved processing ease. The polybutadiene, a rubbery substance, provides toughness and ductility at low temperatures, at the cost of heat resistance and rigidity. For the majority of applications, ABS can be used between −20 and 80 °C (−4 and 176 °F), as its mechanical properties vary with temperature. The properties are created by rubber toughening, where fine particles of elastomer are distributed throughout the rigid matrix.

3.3 3D PRINTING OF ABS

When extruded into a filament, ABS plastic is a common material used in 3D printers, as it is cheap, strong, has high stability and can be post-processed in various ways (sanding, painting, gluing, filling and chemical smoothing). When being used in a 3D printer, ABS is known to warp due to shrinkage that occurs while cooling during the printing process.

The shrinking can be reduced by printing inside an enclosure on a heated print surface, using an adhesive such as a glue stick or hairspray to ensure the first layer of the print is well stuck to the print surface, or printing with a brim/raft at the base of the print to help increase adhesion to the print surface. ABS is only used in FFF/FDM 3D printers, as resin 3D printers cannot melt plastic.

Particular forms of ABS filaments are ABS-ESD (electrostatic discharge) and ABS-FR (fire resistant), which are used in particular for the production of electrostatically sensitive components and refractory prefabricated parts.

Physical Properties	Metric
Density	0.882 – 3.50 g/cc
Water Absorption	0.0250 – 2.30 %
Moisture Absorption at Equilibrium	0.100 – 0.300 %
Water Absorption at Saturation	0.100 – 1.03 %
Maximum Moisture Content	0.0100 – 0.150
Linear Mold Shrinkage	0.00150 – 0.0290 cm/cm
Linear Mold Shrinkage, Transverse	0.00200 – 0.00900 cm/cm
Melt Flow	0.0800 – 125 g/10 min

Table 3.1 Physical properties of ABS

Mechanical Properties	Metric
Hardness, Rockwell M	53.0 – 82.0
Hardness, Rockwell R	13.0 – 122
Hardness, Shore D	68.0 – 103
Ball Indentation Hardness	70.0 – 120 Mpa
Tensile Strength, Ultimate	2.60 – 73.1 Mpa
	20.0 – 43.0 Mpa @Temperature 60.0 – 90.0 °C
Tensile Strength, Yield	2.00 – 77.0 Mpa
Elongation at Break	1.40 – 110 %
Elongation at Yield	1.70 – 40.0 %
Modulus of Elasticity	0.778 – 6.10 Gpa
Flexural Yield Strength	10.3 – 655 Mpa
Flexural Modulus	0.0241 – 6.89 Gpa
	1.50 – 4.00 Gpa @Temperature 60.0 – 90.0 °C
Poisson’s Ratio	0.360 – 0.380

Table 3.2 Mechanical Properties of ABS

Thermal Properties	Metric
CTE, linear	7.90 – 900 µm/m-°C
CTE, linear, Transverse to Flow	81.0 – 100 µm/m-°C
Specific Heat Capacity	1.60 – 2.13 J/g-°C
Thermal Conductivity	0.128 – 0.187 W/m-K
	0.250 – 0.250 W/m-K @Temperature 30.0 – 260 °C
Maximum Service Temperature, Air	50.0 – 109 °C
Hot Ball Pressure Test	75.0 – 105 °C
Deflection Temperature at 0.46 Mpa (66 psi)	56.0 – 120 °C
Deflection Temperature at 1.8 Mpa (264 psi)	65.0 – 220 °C
Vicar Softening Point	45.0 – 135 °C
Heat Distortion Temperature	76.4 – 87.8 °C
Glass Transition Temp, Tg	105 – 109 °C
UL RTI, Electrical	50.0 – 120 °C
UL RTI, Mechanical with Impact	50.0 – 105 °C
UL RTI, Mechanical without Impact	50.0 – 120 °C
Flammability, UL94	HB – 5VA
Oxygen Index	19.0 – 30.0 %
Glow Wire Test	600 – 960 °C

Table 3.3 Thermal Properties of ABS

3.4 MODELING

3.4.1 SOFTWARE

SolidWorks is a solid modelling computer-aided design and computer-aided engineering application published by Dassault Systems.

SolidWorks is a solid modeler, and utilizes a parametric feature-based approach which was initially developed by PTC (Creo/Pro-Engineer) to create models and assemblies. The software is written on Parasolid-kernel.

Parameters refer to constraints whose values determine the shape or geometry of the model or assembly. Parameters can be either numeric parameters, such as line lengths or circle diameters, or geometric parameters, such as tangent, parallel, concentric, horizontal or vertical, etc. Numeric parameters can be associated with each other through the use of relations, which allows them to capture design intent.

Design intent is how the creator of the part wants it to respond to changes and updates. For example, you would want the hole at the top of a beverage can to stay at the top surface, regardless of the height or size of the can. SolidWorks allows the user to specify that the hole is a feature on the top surface, and will then honor their design intent no matter what height they later assign to the can.

Features refer to the building blocks of the part. They are the shapes and operations that construct the part. Shape-based features typically begin with a 2D or 3D sketch of shapes such as bosses, holes, slots, etc. This shape is then extruded to add or cut to remove material from the part. Operation-based features are not sketch-based, and include features such as fillets, chamfers, shells, applying draft to the faces of a part, etc.

Building a model in SolidWorks usually starts with a 2D sketch (although 3D sketches are available for power users). The sketch consists of geometry such as points, lines, arcs, conics (except the hyperbola), and splines. Dimensions are added to the sketch to define the size and location of the geometry. Relations are used to define attributes such as tangency, parallelism, perpendicular, and concentricity. The parametric nature of SolidWorks means that the dimensions and relations drive the geometry, not the other way around. The dimensions in the sketch can be controlled independently, or by relationships to other parameters inside or outside the sketch.

In an assembly, the analog to sketch relations are mates. Just as sketch relations define conditions such as tangency, parallelism, and concentricity with respect to sketch geometry, assembly mates define equivalent relations with respect to the individual parts or components, allowing the easy construction of assemblies. SolidWorks also includes additional advanced mating features such as gear and cam follower mates, which allow modelled gear assemblies to accurately reproduce the rotational movement of an actual gear train.

Finally, drawings can be created either from parts or assemblies. Views are automatically generated from the solid model, and notes, dimensions and tolerance

SOLIDWORKS focuses on quickly creating 3D solid models of your design, rapidly creating both complex parts and assemblies on screen in 3D as oppose to flat 2D drawings which in turn leads to:

- Faster design development and detailing
- Improved visualization and communication
- Assess design functionality and performance prior to prototype production
- Auto generated manufacturing data for 3D solid models which use programming CNC machine tools and rapid prototyping equipment.

With all drawing views generated from the original 3D model SOLIDWORKS ensures any amendments made to the model are automatically updated within the drawing. This automatic associativity guarantees your solid model is always accurately reflected within in your drawings.

Key SOLIDWORKS 3D solid modelling features enable you to:

- Produce 3D solid models of any part and assembly, regardless of size and complexity.
- Synchronize all 3D models, 2D drawings and other design and manufacturing documents thanks to inbuilt associativity which automatically tracks for any changes and makes updates.
- Quickly amend designs by controlling key design parameters.
- Create surfacing for any 3D geometry regardless of complexity or stylization.
- Produce in depth 3D model analysis instantly on an extensive range of properties: mass, density, moments of inertia.

3.4.2 MODELLING

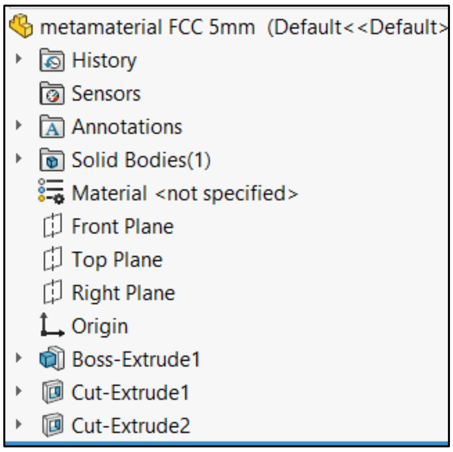


Fig 3.1 Specification Tree

Initially I drew 2D sketch of required geometry Boss extrude it to create 3D Model of required length.

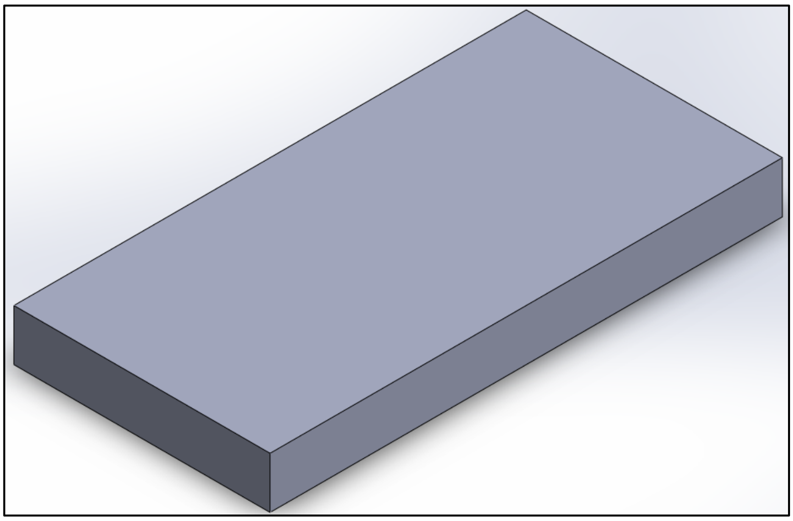


Fig 3.2 Boss-Extruded Solid

Later select a surface of the body where we want draw 2D geometry.

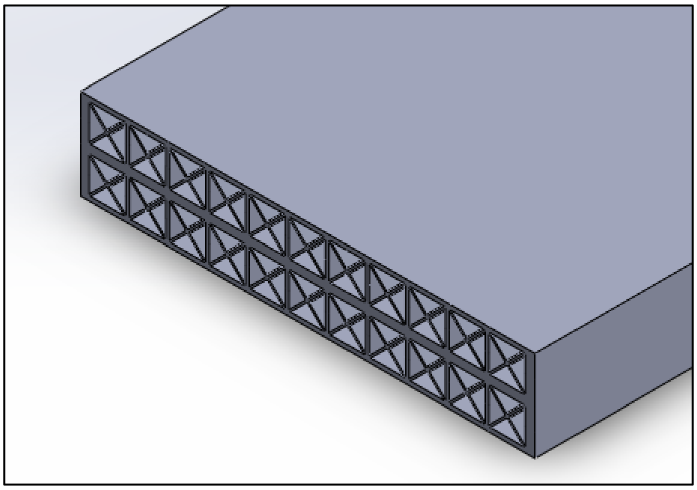


Fig 3.3 Cut-Extruded Solid

After that we Cut Extrude the 2D geometry from body to form micro architecture of required shape.

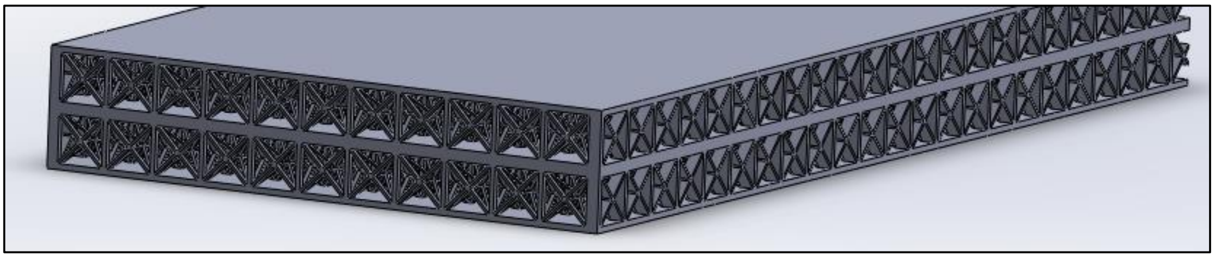


Fig 3.4 Double Cut-Extruded Solid

CHAPTER-IV

ANALYSIS

4.1 THERMAL ANALYSIS

4.1.1 STEADY-STATE THERMAL ANALYSIS

For this example, we will be setting it up as a steady-state thermal analysis, which means there is no time factor involved.

1. We will start by creating a new Thermal Study.
2. Then we are going to define the heat power of the microchip. To do this:
    a. Right-click on Thermal **Loads,** and select Heat **Power**
    b. Use the Feature Manager flyout tree to select the microchip part
    c. Set the Heat Power to be 60 W

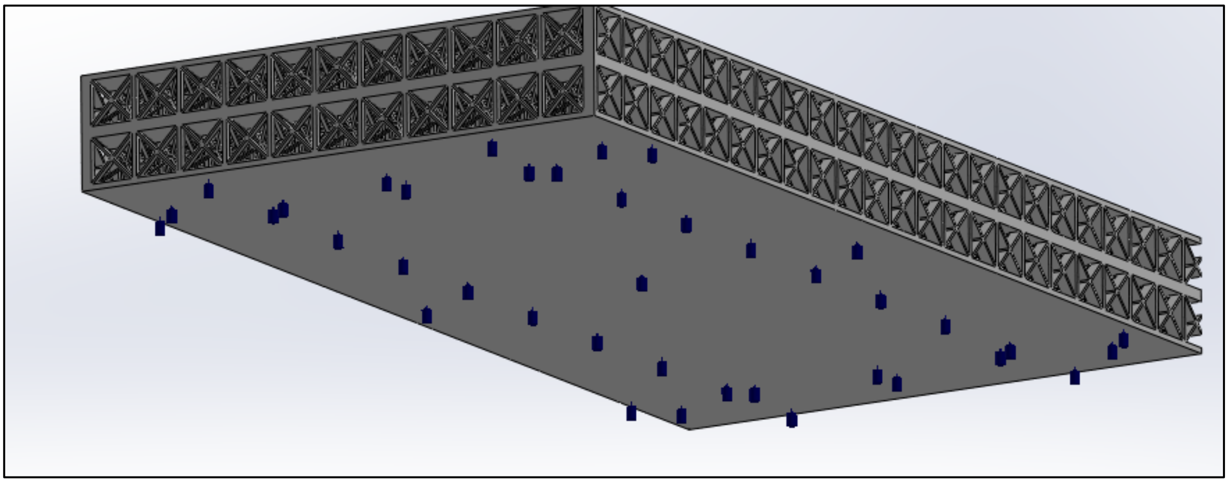


Fig 4.1 Heat Power Input

3. We now need to define the convection that is coming off of the rest of the faces on the heat sink. Because the connectors are insulated, we don't need to define those.
    a. Right-click on Thermal **Loads and** select Convection**.**
    b. Select all the exposed faces of the heat sink.
    c. Define the Convection Coefficient as 250 W/ (m^2.K)
    d. Define Bulk Ambient Temperature (the temperature that surrounds the model) as 300 Kelvin (K)

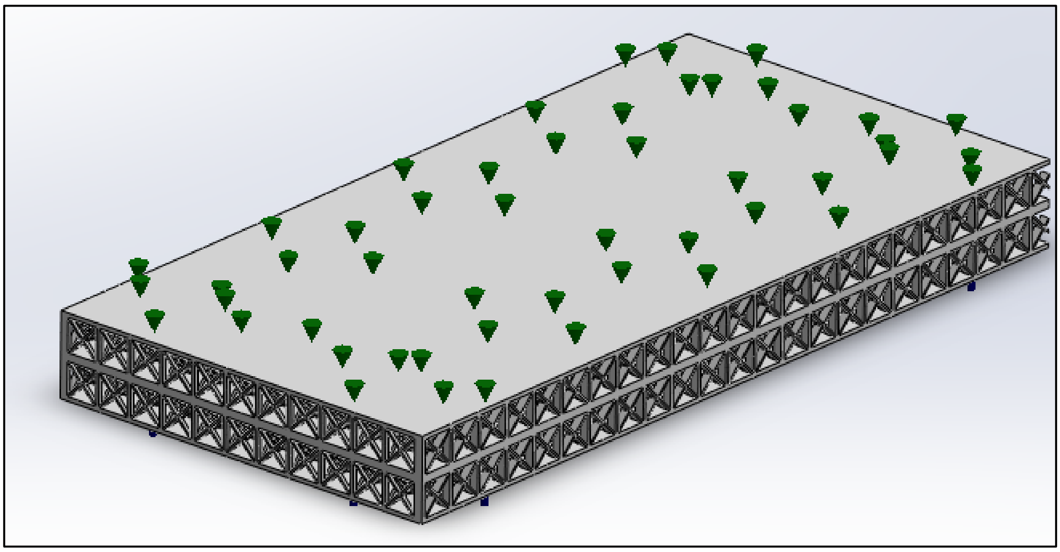


Fig 4.2 Convectional Heat Transfer

e. Accept that, and start a new Convection for the exposed faces of the microchip.
f. Convection Coefficient is 100 W/(m^2.K), Bulk Ambient Temperature is 300 Kelvin (K).

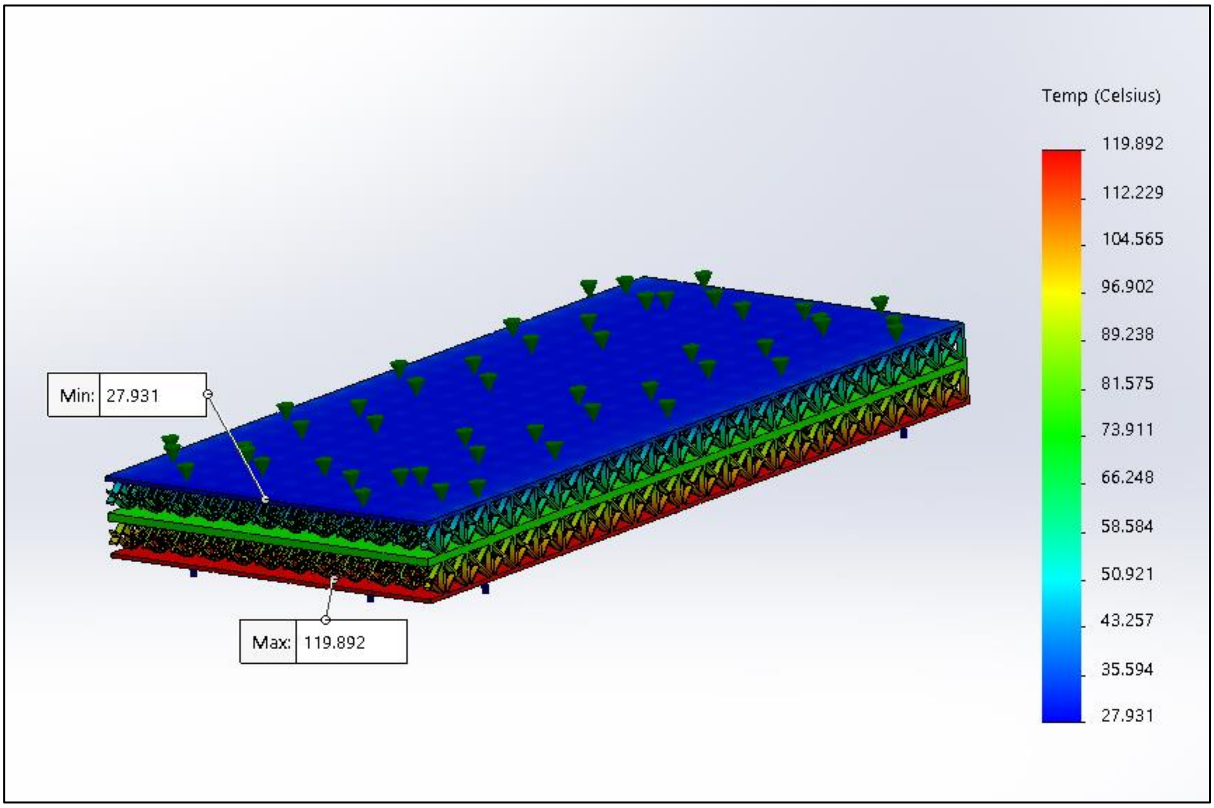


Fig 4.3 Max & Min Temperatures

4. We can now run the study and analyze the results.

4.2 FLOW ANALYSIS

4.2.1 INTERNAL FLOW ANALYSIS

PCB enclosures, valves, pumps, and manifolds are all examples of internal analysis studies. Because SOLIDWORKS Flow Simulation functions inside of SOLIDWORKS CFD software, setting up computational domains, boundary conditions, and heat sources can be done in minutes. The results of your analysis can be applied directly to your design allowing you to test more iterations in less time.

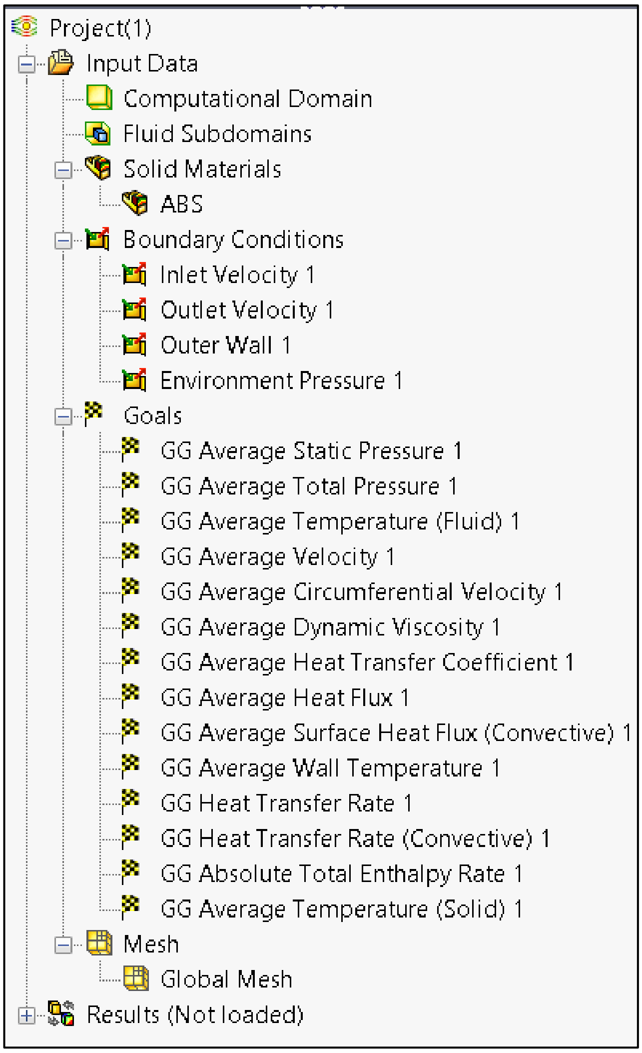


Fig 4.4 Project Specification Tree

SOLIDWORKS Flow Simulation analysis is to prepare the geometry. Let us assume that the analysis we want to complete is an internal analysis and that lids have been placed in the model using the C*reate Lids* tool to enclose the internal volume.

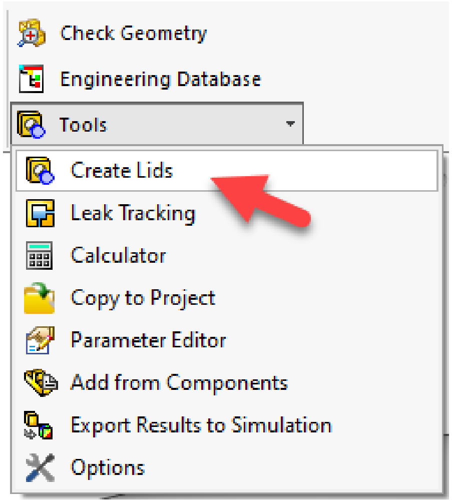


Fig 4.5 Create Lids

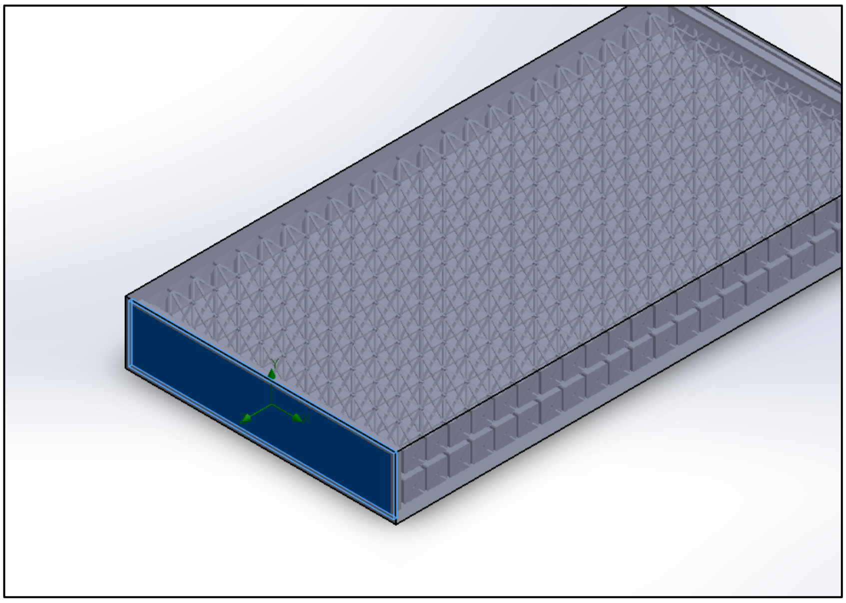


Fig 4.6 3D Flow Model

SOLIDWORKS Flow Simulation provides a Setup Wizard to start your project. The Setup Wizard guides you through the settings you will need to complete a successful Flow study.

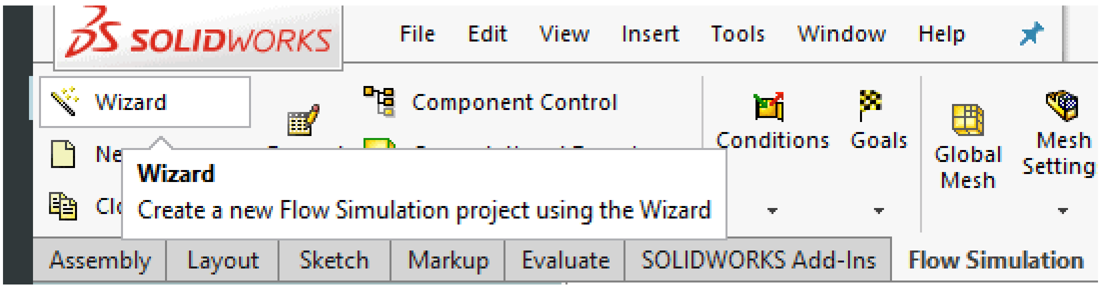


Fig 4.7 Flow Simulation Menu

With the Wizard open, step through the setup choosing the options for the project as you go. Name your project and choose the configuration of the model you wish to analyze. Choose Next to move onto the next step.

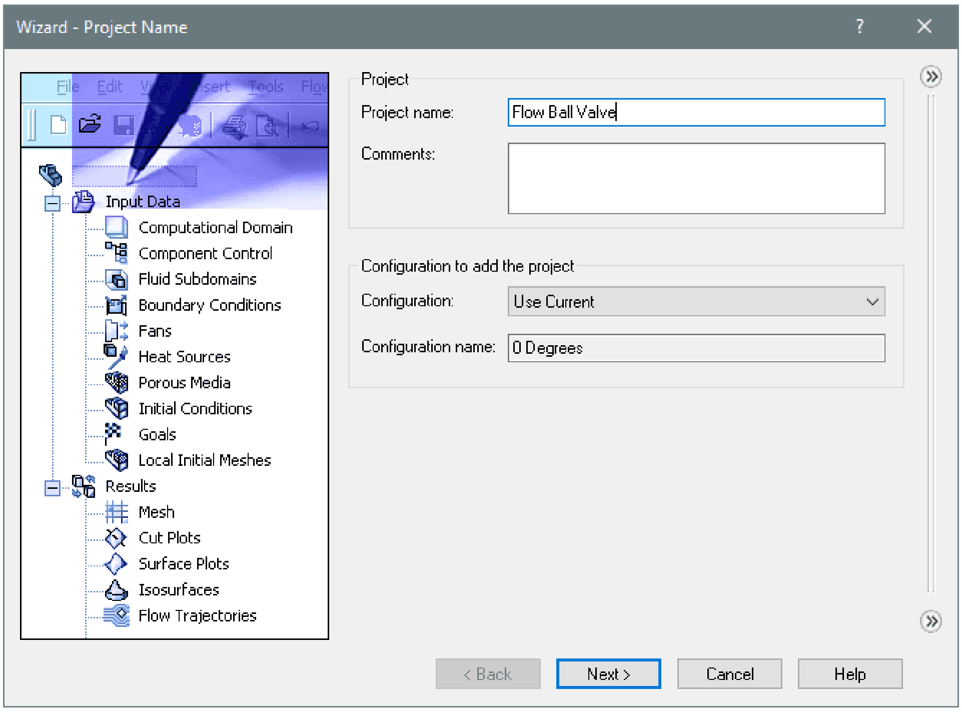


Fig 4.8 Defining Project

Pick the project's Units. Note that you can mix and match units according to your needs.

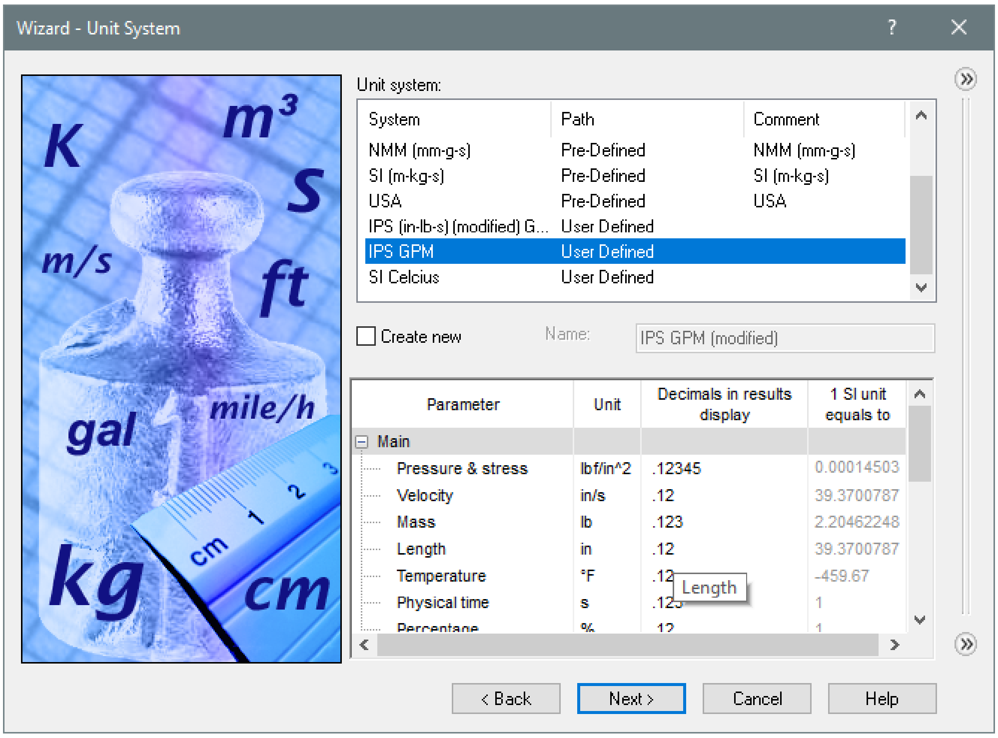


Fig 4.9 Defining Units

Choose the analysis region. Internal analyzes the fluid inside the geometry, external analyzes the fluid outside, and inside the geometry.

Checking the boxes gives you more options for the analysis.

- Heat conduction in solids: turns on the thermal solver and allows for conduction and convection to be calculated.
- Radiation: enables the radiation characteristics of the geometry and accounts for the radiative thermal properties.
- Time dependent: switches from the default steady state to a transient analysis.
- Gravity: enable natural buoyancy effects.
- Rotation: activates the rotating regions capability including, global, local averaging, and sliding.
- Free surface: permits immiscible fluids.

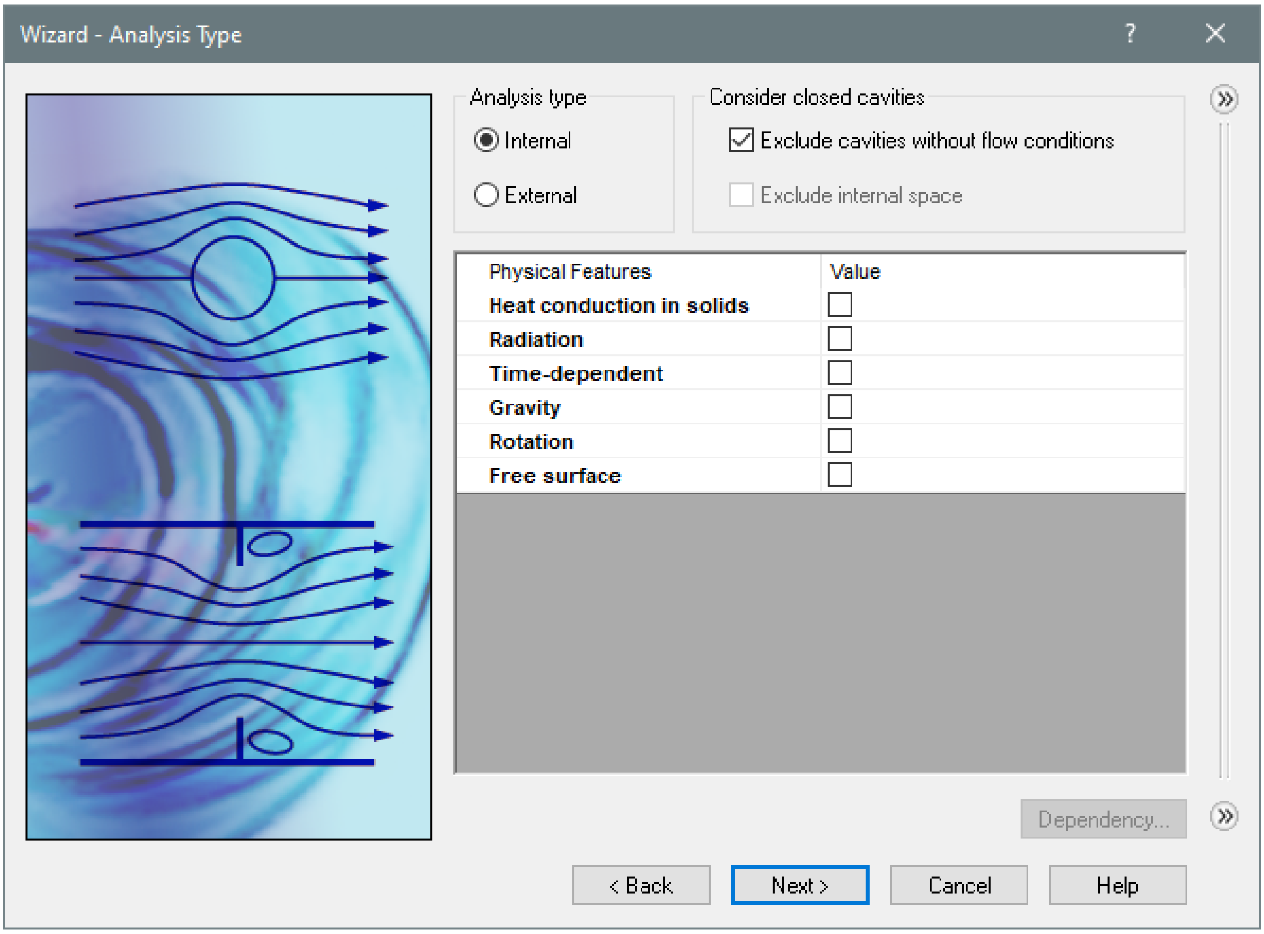


Fig 4.10 Defining Flow Type

We will keep it simple for this analysis by keeping the project internal and steady state.

Next, choose the fluid or fluids you wish to use in the analysis. In this case water was added.

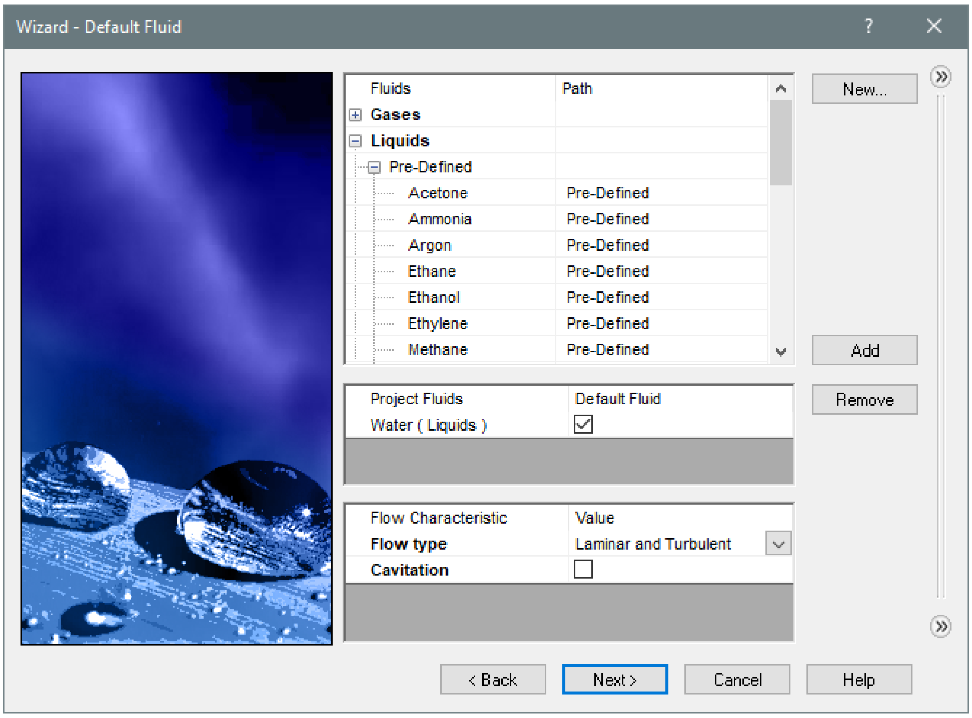


Fig 4.11 Adding Flow to Analysis

The default roughness and wall condition are accepted as they do not affect this analysis.

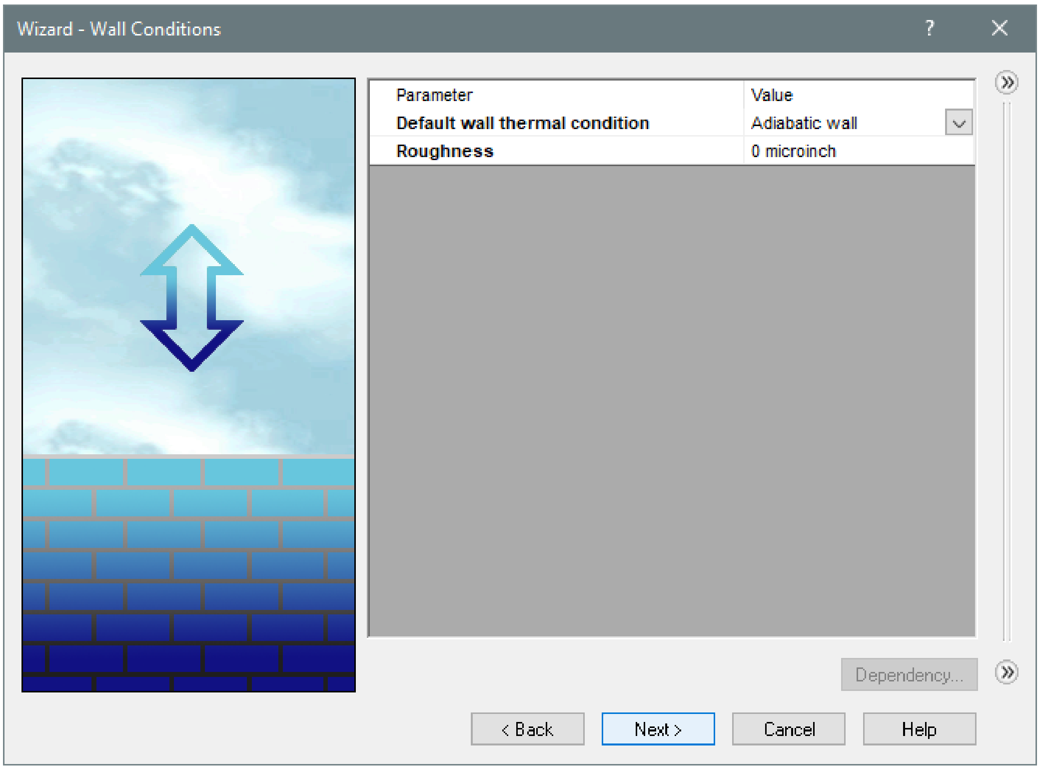


Fig 4.12 Defining wall

The default initial conditions are accepted as well, indicating atmospheric pressure to be at sea level, and room temperature.

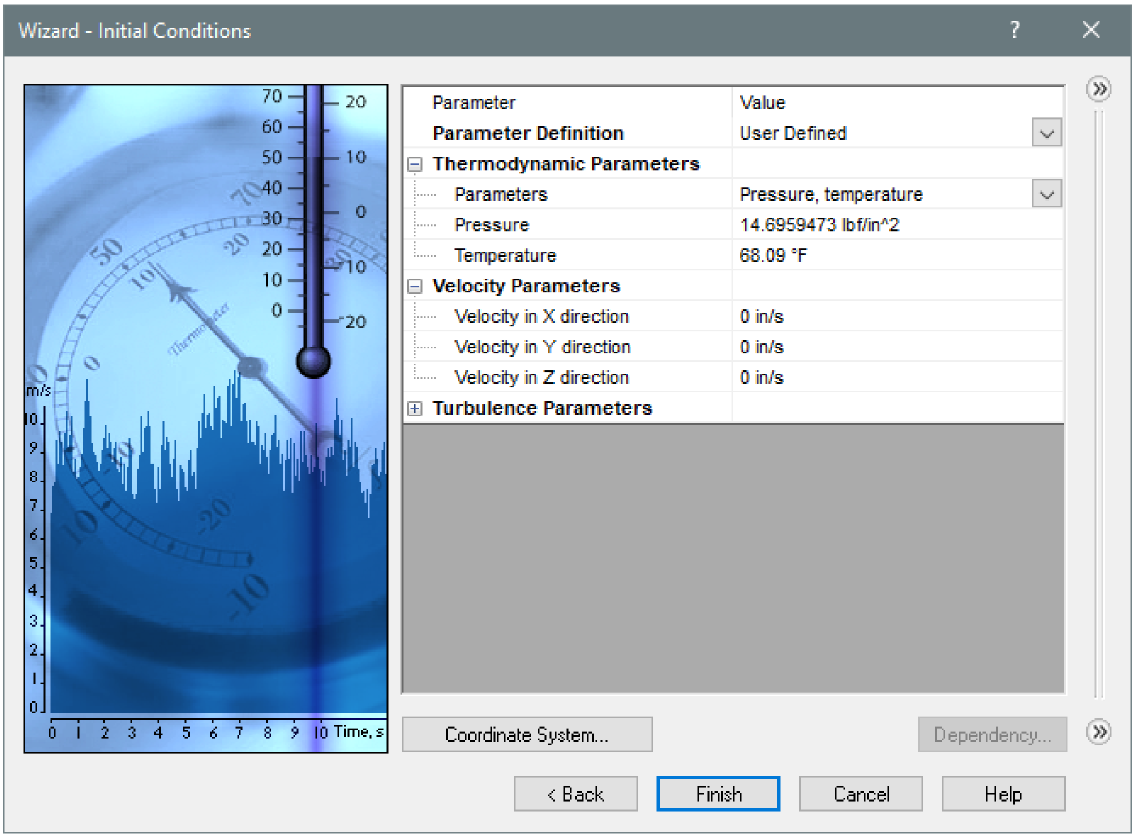


Fig 4.13 Atmospheric Condition

When the Wizard closes, a new project will start located in the Flow Simulation tab of the feature manager tree.

Add the boundary conditions that apply to your project's problem statement. In this case a 1m/s flow rate of water enters the valve and exits through the opposite opening at environmental pressure.

a

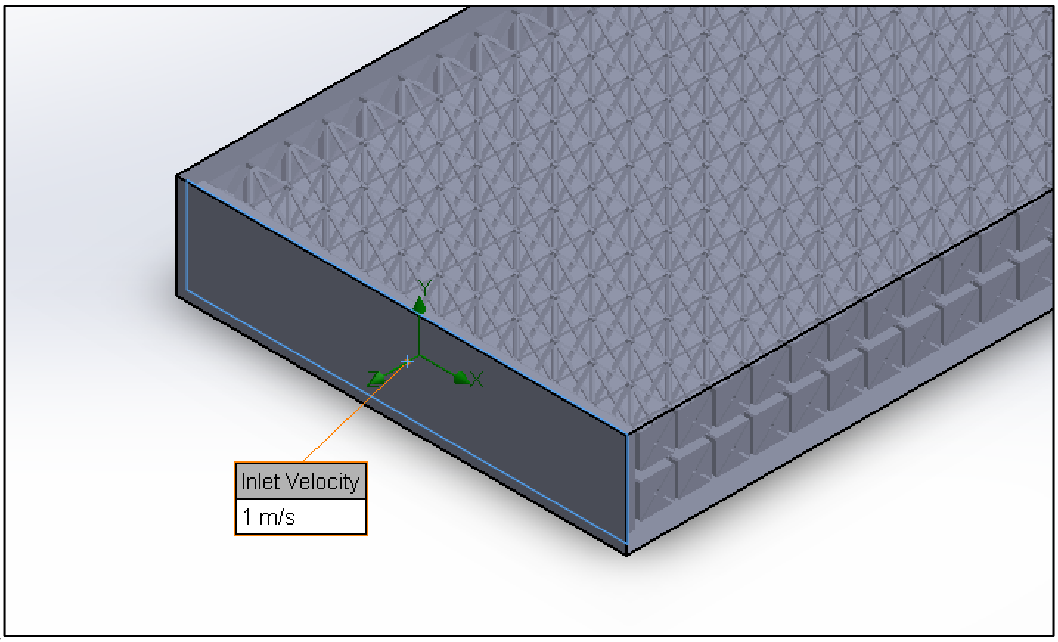


Fig 4.14 Boundary Condition

Assign goals to monitor important output values such as volume flow rate, velocity, and pressure.

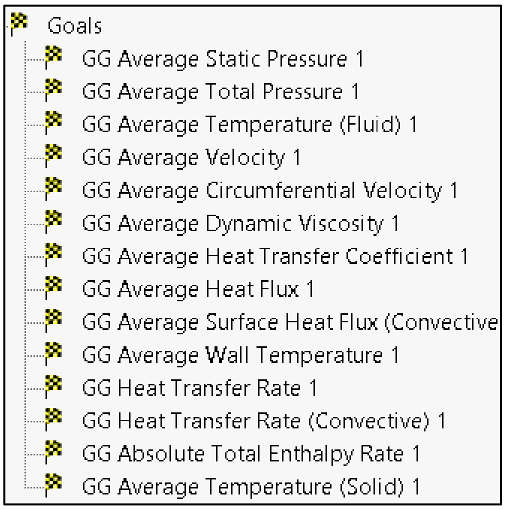


Fig 4.15 Goal Plot

To get the results:

In the Flow Simulation analysis tree, right-click the **Results** icon and select one of the following commands:

- **Load** to load the final results,
- **Load from File** to load results from the selected file,
- **Load Time Moment** to load time-dependent results corresponding to the selected physical time moment.

To quickly animate the time-dependent results in the graphics area, specify the **Selected Parameters** before calculations and use the **Transient Explorer**.

You can select to use the scientific notation for displaying extremely large or small numbers in analysis results. To adjust the use of scientific notation, expand the **Unit notation for results display** item under **Unit Options** in the **General Options** dialog.

The following features are available for visualization and analysis of the calculation results:

Mesh - displaying the computational mesh.

Cut Plot - displaying a section view of a parameter distribution.

Surface Plot - displaying a parameter distribution on the selected model faces or surfaces.

Isosurfaces - displaying a surface along which the selected parameter is constant.

Flow Trajectories - displaying flow trajectories as flow streamlines.

Particle Study - displaying trajectories of physical particles and obtain various information about the particle's behaviour.

Point Parameters - displaying parameter values at specified points.

Surface Parameters - displaying parameter values (minimum, maximum, average and integral) calculated over the specified surface.

Volume Parameters - displaying parameter values (minimum, maximum, average, bulk average and integral) calculated within the specified volumes.

XY Plot - displaying parameter distribution along the specified direction or path.

Goal Plot - displaying goal changes in the course of the calculation.

FFT Plot - displaying time-dependent data using the Fast Fourier Transform (FFT) algorithm.

Flux Plot - displaying heat fluxes between model components and project features as a network chart.

Report - generating analysis report.

Animation - displaying how a distribution of the selected parameter develops with time or changes through the model.

Export Results - exporting the calculated results to the text file for analyzing and visualizing.

To display a list of things you can do with the existing feature, in the Flow Simulation analysis tree right-click the desired item (see **Working with Features** for details). Use **Flow Simulation Results** toolbar that provides quick access to the most frequently used commands.

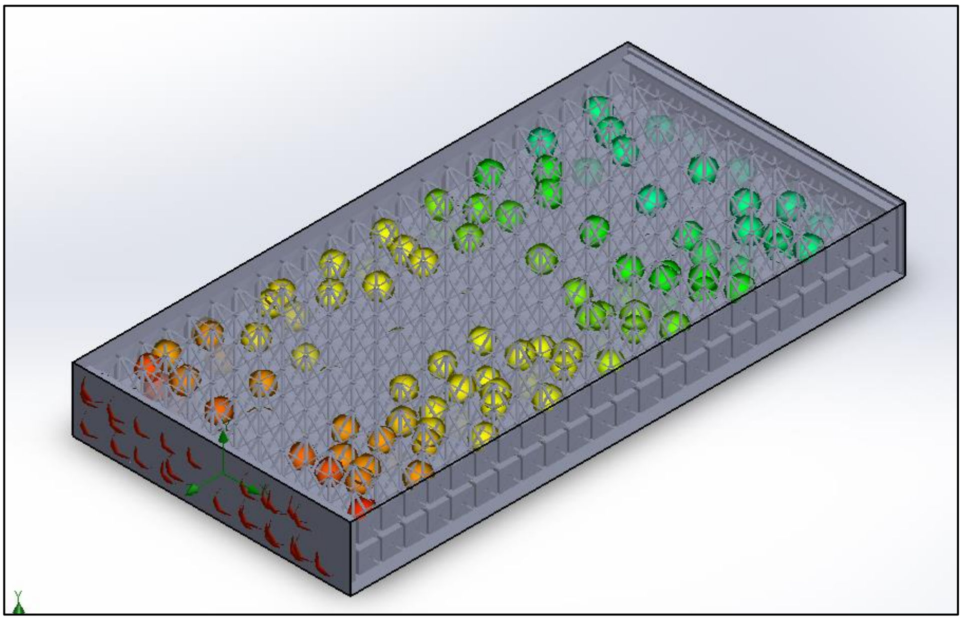


Fig 4.16 Flow Trajectories

The above figure shows the streamlines of fluid flow with variation in color representing the variation in parameters like pressure, temperature, etc.

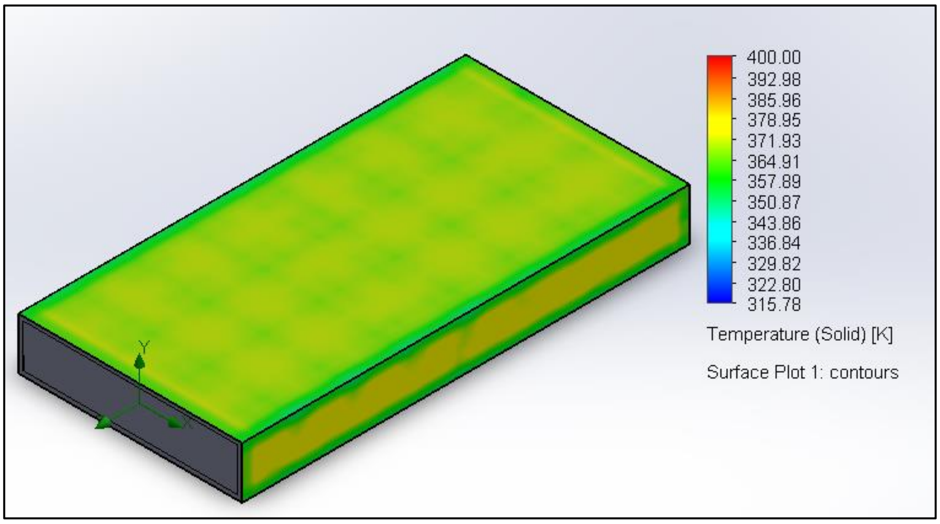


Fig 4.17 Surface Plot

This figure has the parametric variation on the surface of the solid

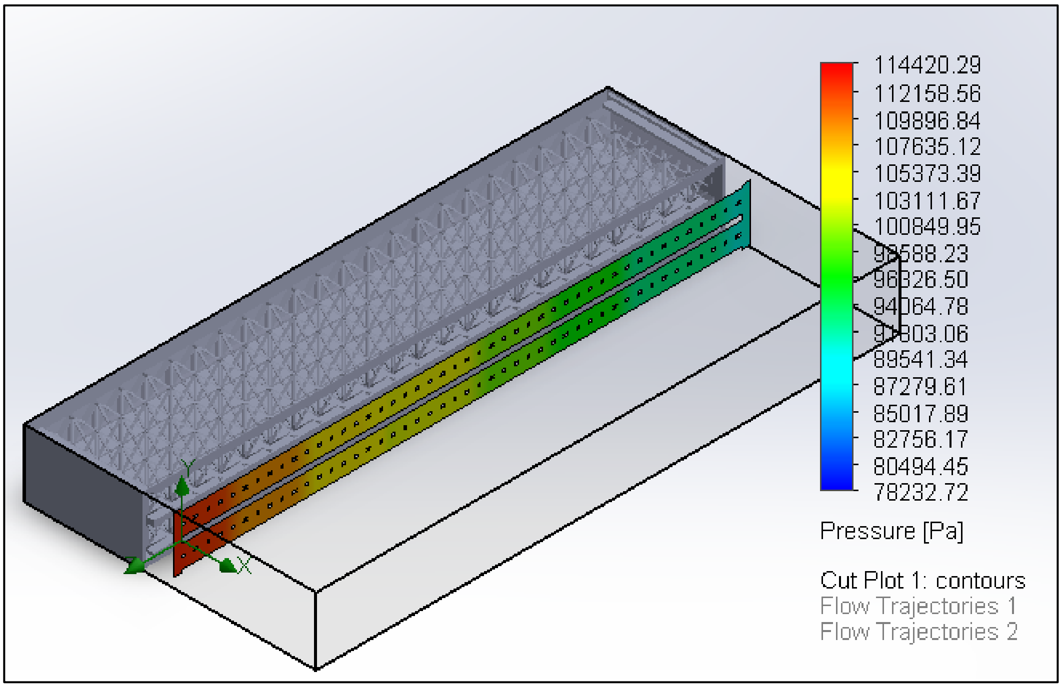


Fig 4.18 Cut Plot

This figure has the section view of the variation of pressure in fluid internally.

CHAPTER-V

TESTING

5.1 THERMAL CONDUCTIVITY

What is Thermal Conductivity?

Fourier's law of thermal conduction also known as the law of heat conduction is very relevant for heat transfer computation. This principle is applicable for heat transfer between two isothermal planes.

It states that the rate at which heat is transferred through a given material is proportional to the negative value of the temperature gradient. And it is also proportional to the area through which the heat flows, but inversely proportional to the distance between the two isothermal planes.

The Formula for Thermal Conductivity

Every substance has its own capacity for conducting and transferring the heat. The thermal conductivity of a material is explained by the following formula:

$K = Q\, d/A\Delta T$

Also, the above formula can be rearranged to give the value of transfer of heat, as follows:

$Q = K \times A \times (THOT - TCOLD)\ /d$

The SI unit of this quantity is watts per meter-Kelvin or Wm-1K-1. These units will describe the rate of conduction of heat through the material having the unit thickness and for each Kelvin of temperature difference.

TYPES IN THERMAL CONDUCTIVITY

There are a number of methods to measure thermal conductivity. In general, there are two basic techniques for measuring thermal conductivity: steady-state methods and transient or non-steady-state methods. Each of these methods is suitable for a limited range of materials, and they are based on the fundamental laws of heat conduction and electrical analogy. Steady-state methods have been traditionally used since they are mathematically simpler. There is an important distinction between steady-state and transient techniques. Transient heat transfer methods are capable of directly determining thermal diffusivity, whereas steady-state methods are considered to be more accurate than transient methods for testing dry materials.

The steady-state technique records a measurement when a tested material's thermal state reaches complete equilibrium. A steady-state condition is attained when the temperature at each point of the specimen is constant and the temperature does not change with time. A disadvantage, however, is that it generally takes a long time to reach the required equilibrium. The method involves expensive method apparatus since a well-designed experimental installation system is usually needed. Nevertheless, it is the primary and most accurate measurement method.

The non-steady-state or transient technique records a measurement during the heating process. The method determines thermal conductivity properties by means of transient sensors. These measurements can be made relatively quickly, which garners an advantage over steady-state techniques. For this reason, numerous solutions have been derived for the transient heat conduction equation by using one-, two-, three-dimensional geometries. Transient methods generally employ needle probes or wires.

Compared to electrical and thermal transport, the ratios of thermal conductivities of the best conduction and insulation conditions are significative and determinative magnitudes. Therefore, instruments for thermal property identification are often designed only for specific kinds of materials or temperature ranges. Table 1 presents a comparison of the most common methods of thermal conductivity measurement. Measurement systems can also be divided into three categories based on the operating temperature of the apparatus: (1) room temperature operation (20–25°C), (2) below room temperature operation (down to about –180°C), and (3) high-temperature operation (up to 600°C or above). A given measurement system is often optimized for one of these temperature ranges.

→ steady-state technique

1. Guarded hot plate.
2. Heat-flow meters.
3. Direct heating method.
4. Pipe method.

→ non-steady-state or transient.

1. Hot-wire method
2. Hot-disk method
3. Laser flash method
4. The 3-ω method
5. Fitch method
6. Photothermal methods

-------WE USE GUARDED HOT PLATE METHOD FOR MATERIAL TESTING----

5.2 GUARDED HOT PLATE

The guarded hot plate, also known as the Peonage apparatus, is the most commonly used and most effective method for measuring the thermal conductivity of insulation materials. The GHP relies on a steady temperature difference over a known thickness of a specimen and its primary purpose is to control the heat flow through the material. One disadvantage is that establishing a steady-state temperature gradient through a specimen is time-consuming when using the GHP and other steady-state techniques. Other potential disadvantages are that the temperature gradient must be relatively large, the specimen width must be large, and also that the contact resistance between the thermocouple and the specimen surface poses a major source of error. Although Reference cites large specimen size as a potential disadvantage, size is usually not a serious issue.

The experimental setup of the guarded hot plate employs a steady-state heat transfer between a hot plate and a cold plate. However, the accuracy of this method is questionable, interlaboratory comparisons of GHP calculations have revealed discrepancies among 20 different GHPs used at different times. The individual results of these 20 GHPs diverged significantly from reference values, ranging from +13 to −16%.

Despite these disadvantages, the standardized GHP method is the ideal apparatus for researchers and scientists in the field of insulation testing and it is considered an absolute measurement method. The practical applicability requires careful consideration of the array content: (a) attaining steady-state conditions; (b) the unidirectional heat flow in the area under analysis, the temperatures of the hot and cold surfaces, and the specimens' thickness; and (c) other factors influencing the unidirectional heat flow.

The construction of the guarded hot plate

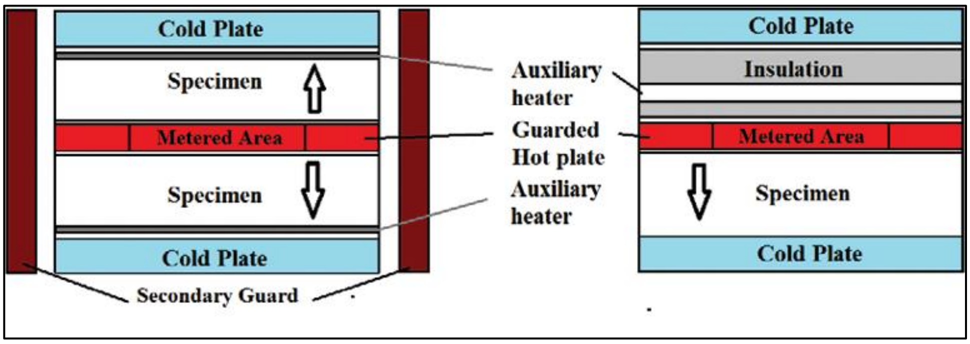


Fig 5.1 Guarded Plate Method

The apparatus of guarded hot-plate method for thermal conductivity measurement. (a) two specimens with/without auxiliary heaters and secondary guards, (b) single-specimen.

The guarded hot-plate measurements are analyzed on the fundamental of the heat transfer in the infinite slab geometry. Since specimen dimensions are finite, unidirectional heat flow is achieved through the use of guard heaters. The temperature of a thermal guard is maintained at the same temperature as its adjacent surface (which is considered as an auxiliary heater/heat sink), in order to prevent heat loss from the specimen and heat source/heat sink, and as a result, unidirectional heat flow is attained. After a steady state is reached, the heating and cooling plates have stable temperatures. Then the thermal conductivity can be determined based on the heat input, the temperature difference through the specimen, the thickness of the specimen, and the size of the metered area of heat transfer. Steady-state conditions may change with respect to specimen type, specimen size, and mean temperature. The GHP is most suitable for dry homogeneous specimens, but it is unsuitable for materials in which there is a potentiality for moisture migration.

The guarded hot-plate setup is comprised of cold plates, a hot plate, a system of guard heaters, and thermal insulation. Hot plate is electrically heated and the cold plates are Peltier coolers or liquid-cooled heat sinks. The configuration is arranged symmetrically, with guarded hot plates located on the sides while the heater unit is sandwiched between two specimens or a single specimen and an auxiliary layer (Figure). The different types of guarded hot-plate apparatus are shown in Figure. In the single-sided system state, the heat flow passes through one specimen, while the top of the main heater acts as an insulating guard, thus ensuring an adiabatic environment.

In the two-specimen apparatus, the main advantage is that heat loss from the hot plate can be controlled more effectively due to the symmetrical arrangement of the specimen on each side of the heater. Unlike the single-specimen method, the symmetrical setup can be used for investigating solid materials. For measuring the conductivity of nonsolid materials, it is necessary to heat the specimen from the top in order to avoid convection.

The electrical heating is placed into the plates in a certain shape or form, such as a square or a circular shape. The guarded plate (ring), the central plate (metered area), and the auxiliary heater can all be arranged in this manner. The apparatus must test two specimens simultaneously in the form of a slab with a standard size (such as 300 mm × 300 mm or different sizes). A fixed heat rate must be applied by an electric heater. This arrangement produces a heat flow across the two specimens, flowing outward toward two plates chilled by a Peltier or a liquid cooling system.

These heat measurements are recorded by differential thermocouples, which are instruments that control a flat electrically heated metering area that is surrounded on all lateral sides by a guard heater section. The heated section provides the planar heat source applied to the hot face of the specimens. Heat is supplied to the metered area (the central heater) at an assigned heat power rate. The temperature of the guard heater is maintained at the same temperature as the metered section by using a control system. The adjacent thermal guard surfaces and/or plates are held at the same temperature range, and ideally no heat leakage occurs from the source, the specimen, or the boundaries. This is aimed at ensuring a one-dimensional thermal heat flow in the actual and practical test section, corresponding solely to the central metered heater. In addition, the apparatus is surrounded by thermal insulation, as well as guard heaters. And, the hot/cold metal parts are positioned between the heaters/cooling plates and each specimen. The parts matched the same frame design are adjacent to the related side (hot or cold) temperature sensors. A data acquisition system is connected to the temperature sensors and the electrical power supply devices, which are in turn controlled by a closed-loop control system.

PRINCIPLE OF OPERATION

The specimens of the homogeneous material with the same thickness are interposed between the hot guard heaters and the cold plates. For two specimen apparatuses, the auxiliary heaters may be placed above and below the specimens. A well-defined, user-selectable temperature difference is established between the hot and the cold plates. The power rate input in the hot plate with metered area A is measured when thermal equilibrium is reached at steady-state conditions. When the control system is used, the plate temperatures reach stability.

It is assumed that the measured heat power rate is transferred across the specimen due to guarded heaters. After thermal equilibrium has developed and the heating and cooling plates are kept in stable temperatures, the thermal conductivity can be calculated from the input values. The input values are the heat power Q, the temperature differential across the specimen (T hot − T cold), the specimen thickness

(Δx), and the heat transfer area (center metered area, A). The thermal conductivity is computed by measuring the quantity of heat input under the steady-state temperature profile in the entire specimen. From the measured input values, the effective thermal conductivity can be calculated using the following unidirectional steady-state heat transfer equation:

$K_{eff} = Q\Delta x / 2A.\Delta T$

where the heat flow Q is obtained by measuring a power P (or half power for two specimen) generated in an electrical heater. The heat conduction equation for homogenous isotropic materials without using internal heat generation is given for the steady state in Eq. (1). These methods depend on Fourier-Biot law of heat conduction [1, 3, 14]. Its modified equation forms can be used for one-dimensional steady heat flow across different sizes, such as plate, cylinder, and sphere.

For the shapes in cylinder forms, radial heat-flow steady-state methods are observed. The specimen completely encloses the heating source in this method, eliminating end losses. The lateral effects are assumed to be insignificant either because the ratio of length to diameter of the test apparatus is large or because guard heaters are used. It is assumed that the surface of the central heater at a diameter r1 and the outer specimen surface at diameter r2 reach the same temperature after the steady state is established. The thermal conductivity can be determined based on "the heating power, the length of the cylinder, the temperature differential between two internally located sensors, and their radial position". Because of practical application difficulties, the cylinder (and sphere) method is not popular. Nevertheless, this method is applied and used to measure thermal conductivity using the cylinder shape method.

The guarded hot-plate method under a vacuum is based on an absolute measurement method for research and therefore requires no calibration standards. Furthermore, this can be seen as an absolute measurement, regardless of vacuum conditions. The plate system is placed in a vacuum medium. The measurements can be carried out under a vacuum as well as under atmospheric or defined pressure levels. The system requires a symmetry and two specimens for each test. With a guarded heater and/or thermal insulation, a relative uncertainty of 2% for thermal conductivity measurements of can be achieved. Each plate and the guard ring/heater are connected to a separate control system with temperature sensor(s) and an assigned power supply.

The guarded hot-plate and cylinder method exemplify a measurement principle that has been optimized for different ranges of thermal conductivity. The guarded hot-plate method can be used to test the thermal properties of nonmetals such as thermal insulation materials, polymers glasses, and ceramics, as well as liquids and gases in the temperature range between about 80 and 800 K. The thermal conductivities of metals (approximately up to 500 W/ (m K) in a temperature range between about 4 and

1000 K) can be tested via the cylinder method of employing axial heat flow. The GHP method is appropriate for these kinds of metal because the determination of the temperature difference is the main challenge when measuring materials with high thermal conductivity (e.g., metals). In these kinds of tests, the contact resistances between the specimen and the heater or the cold plate must be considered.

5.3 TESTING OF HEAT TRANSFER

HEAT TRANSFER

What is meant by heat transfer?

heat transfer, any or all of several kinds of phenomena, considered as mechanisms, that convey energy and entropy from one location to another. The specific mechanisms are usually referred to as convection, thermal radiation, and conduction (see thermal conduction).

What are the three types of heat transfer?

Heat is transferred via solid material (conduction), liquids and gases (convection), and electromagnetic waves (radiation). Heat is usually transferred in a combination of these three types and randomly occurs on its own. As a result, it is important to understand those three phenomena taken separately. For instance, the thermal environment of a building is influenced by heat fluxes through the ground (conduction), and the building envelope (mostly convection and radiation).

CONVECTION

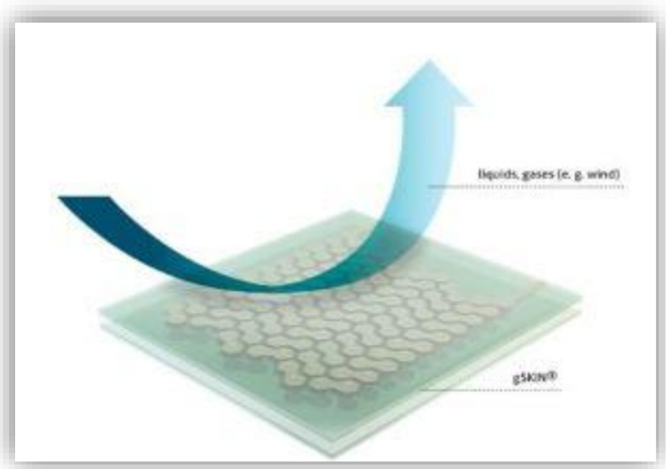


Fig 5.2 Convection

Convection, heat flux through liquids and gases

The first type of heat transfer is convection. Convection is heat flux through liquids and gases. Heat Flux Sensors can measure convective heat flux (see picture on the left). Good examples of convective heat flux are:

- Feeling much colder when it is windy.
- Feeling much colder in water of 25°C than in air of 25°C.
- Sensing principle in heat flux-based mass flow sensors.

CONDUCTION

The second type of heat transfer is conduction. Conduction is heat flux through solid materials. Interestingly, Heat Flux Sensors can also evaluate precisely conductive heat flux (see picture on the right hand-side). As an example of conductive heat flux, one can find:

- Touching a hot cup of coffee
- Thermal influences in precision instruments. Learn more
- Measurement of heat output from chemical reactors.

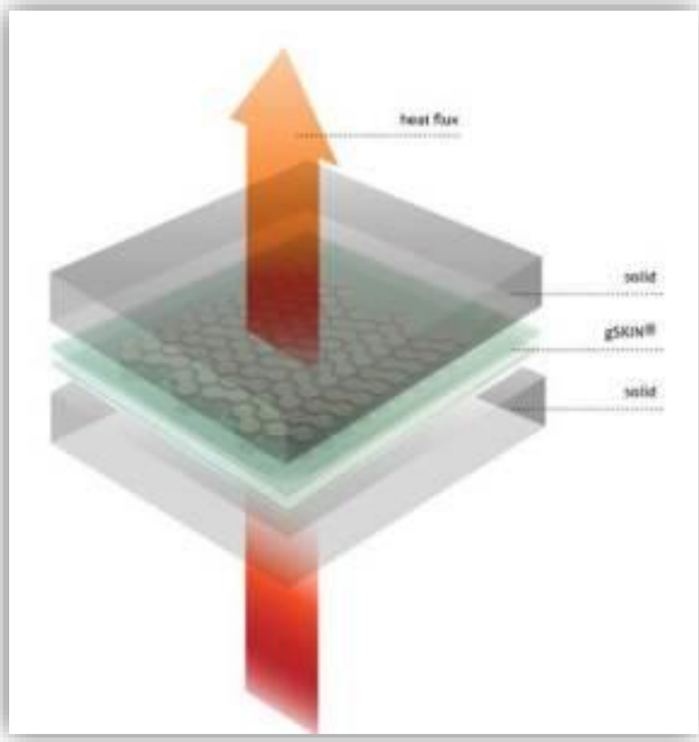


Fig 5.3 Conduction

Conduction, heat transfer through solid materials

RADIATION

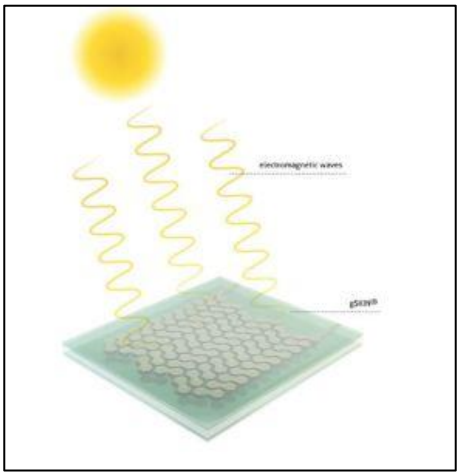


Fig 5.4 Radiation

Radiation, heat flux through electromagnetic waves

The third and last type of heat transfer is radiation. Radiation is heat flux through electromagnetic waves. Lastly, Heat Flux Sensors can assess radiative heat flux. Practically, radiative heat flux can be identified in different phenomena:

- Feeling hot when standing close to fire.
- Measurement of solar power.

5.4 RADIAL HEAT CONDUCTION

The Radial Heat Conduction experiments allows the basic laws of heat transfer by conduction through a cylindrical solid to be investigated.

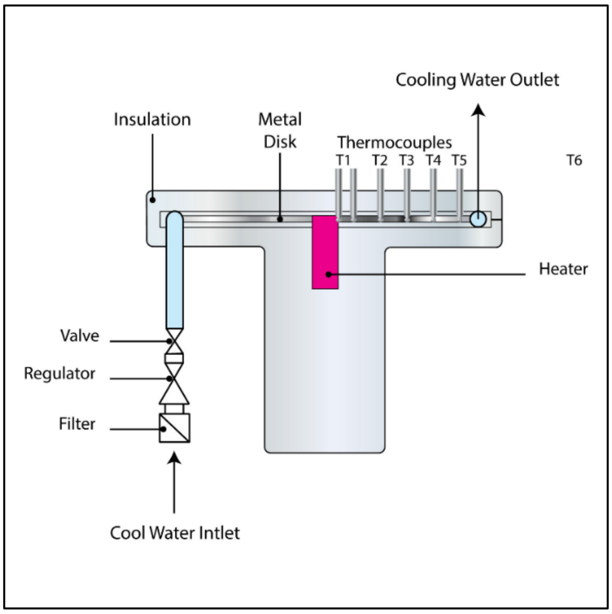
Experimental Set – up the unit is mounted on a plastic base plate that must be placed on a surface, ideally to the left of the Heat Transfer service Unit H112.

Fig 5.5 Radial Heat Conduction Equipment

The heat transfer module comprises an insulated solid disc of brass (3.2mm thick x 110mm diameter) with a brass core (14mm diameter) and an electric heater at the center. The brass disc is water cooled around its circumference. The central heater is nominally rated at 100Watts (at 240 V AC) and an integral high temperature cut out (with automatic reset) prevents overheating. Power is supplied to the heater from the Heat Transfer Service Unit H112 via an 8-pole plug and lead. Six thermocouples T1, T2, T3...T6 are located at increasing radii from the heated center to record the temperature distribution across the disc. The thermocouple sensing tips are located in drilled holes so that in each case the measured point is the Centre of the disc thickness. Each thermocouple is fitted with a miniature plug for direct connection to the Heat Transfer Service Unit H112 and an edge connector for use with HC112A Data Acquisition Upgrade. Water for the cooled circumference is supplied from a local tap via the supplied hoses

Fig 5.6 Heat Transfer Module

Water for the cooled circumference is supplied from a local tap via the supplied hoses. Schematic Representation of Linear Conduction Experiment Unit



:

Fig 5.7 Schematic Representation of Linear Conduction Experiment Unit

CAPABILITIES OF THE RADIAL HEAT TRANSFER UNIT

1. To measure the temperature distribution for steady state conduction of heat energy through the wall of a thick cylinder (Radial energy flow) and demonstrate the effect of a change in heat flow.

2. To understand the use of the Fourier Rate Equation in determining rate of heat flow for steady state conduction of heat energy through the wall of a thick cylinder (Radial energy flow) and using the equation to determine the constant of proportionality (the thermal conductivity k) of the disc material.

3. To observe unsteady state conduction of heat and to use this in observation of the time to reach stable conditions.

OPERATING PROCEDURE OF RADIAL HEAT TRANSFER UNIT

1. Ensure that the main switch is in the off position (the digital displays should not be illuminated). Ensure that the residual current circuit breaker on the rear panel is in the ON position.

2. Turn the voltage controller anti-clockwise to set the AC voltage to minimum. Ensure the Radial Heat Transfer Unit H112B has been connected to the Heat Transfer Service Unit H112.

3. Ensure the cold-water supply and electrical supply are turned on at the source. Open the water tap until the flow through the drain hose is approximately 1.5 liters/minute. The actual flow can be checked using a measuring vessel and stopwatch if required but this is not a critical parameter. The flow has to dissipate up to 100W only.

4. Turn on the main switch and the digital displays should illuminate. Set the temperature selector switch to T1 to indicate the temperature of the heated Centre of the disc. Rotate the voltage controller to increase the voltage to that specified in the procedure for each experiment.

5. Observe the temperature T1. This should begin to increase.

6. Allow the system to reach stability, and take readings and make adjustments as instructed in the individual procedures for each experiment.

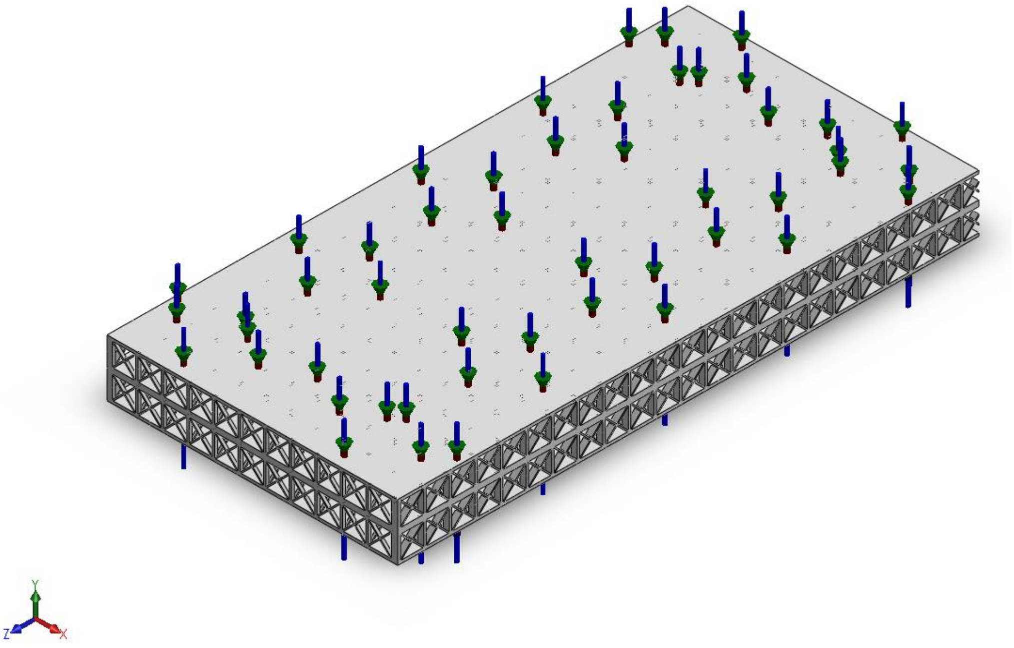
7. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the voltage to zero and allow the system a short time to cool before turning off the cooling water supply.

8. Ensure that the locally supplied water supply isolation valve to the unit is closed. Turn off the main switch and isolate the electrical supply.

CHAPTER-VI

RESULTS AND DISCUSSIONS

6.1 MODEL INFORMATION



Model name: metamaterial FCC 5mm

Fig 6.1

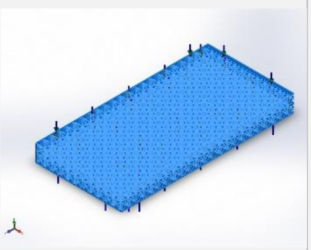
Solid Bodies			
Document Name and Reference	**Treated As**	**Volumetric Properties**	**Document Path/Date Modified**
Cut-Extrude2 	**Solid Body**	**Mass:0.0125028 kg** **Volume:1.22576e-05 m^3** **Density:1,020 kg/m^3** **Weight:0.122527 N**	**C:\Users\JEEVAN\OneDrive\Desktop\meta materials\metamaterial FCC 5mm.SLDPRT** **Jul 4 23:09:52 2022**

Table 6.1 Model Information

6.2 STUDY PROPERTIES

Study name	Thermal 1
Analysis type	Thermal (Steady state)
Mesh type	Solid Mesh
Solver type	FFEPlus
Solution type	Steady state
Contact resistance defined?	No
Result folder	SOLIDWORKS document (C:\Users\JEEVAN\OneDrive\Desktop\meta materials)

Table 6.2 Study Properties

6.3 UNITS

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Table 6.3 Units

6.4 MATERIAL PROPERTIES

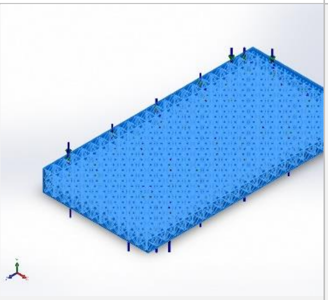
Model Reference	Properties		Components
	**Name:**	ABS	SolidBody 1(Cut-Extrude2)(metamaterial FCC 5mm)
	Model type:	Linear Elastic Isotropic	
	Default failure criterion:	Unknown	
	Thermal conductivity:	0.2256 W/(m.K)	
	Specific heat:	1,386 J/(kg.K)	
	Mass density:	1,020 kg/m^3	
Curve Data:N/A			

Table 6.4 Material Properties

6.5 MESH INFORMATION

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	1 mm
Tolerance	0.05 mm
Mesh Quality Plot	High

Table 6.5 Mesh Information

6.6 MESH INFORMATION – DETAILS

Total Nodes	938090
Total Elements	409924
Maximum Aspect Ratio	15.816
% of elements with Aspect Ratio < 3	54.1
% of elements with Aspect Ratio > 10	0.143
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	01:34:25
Computer name:	

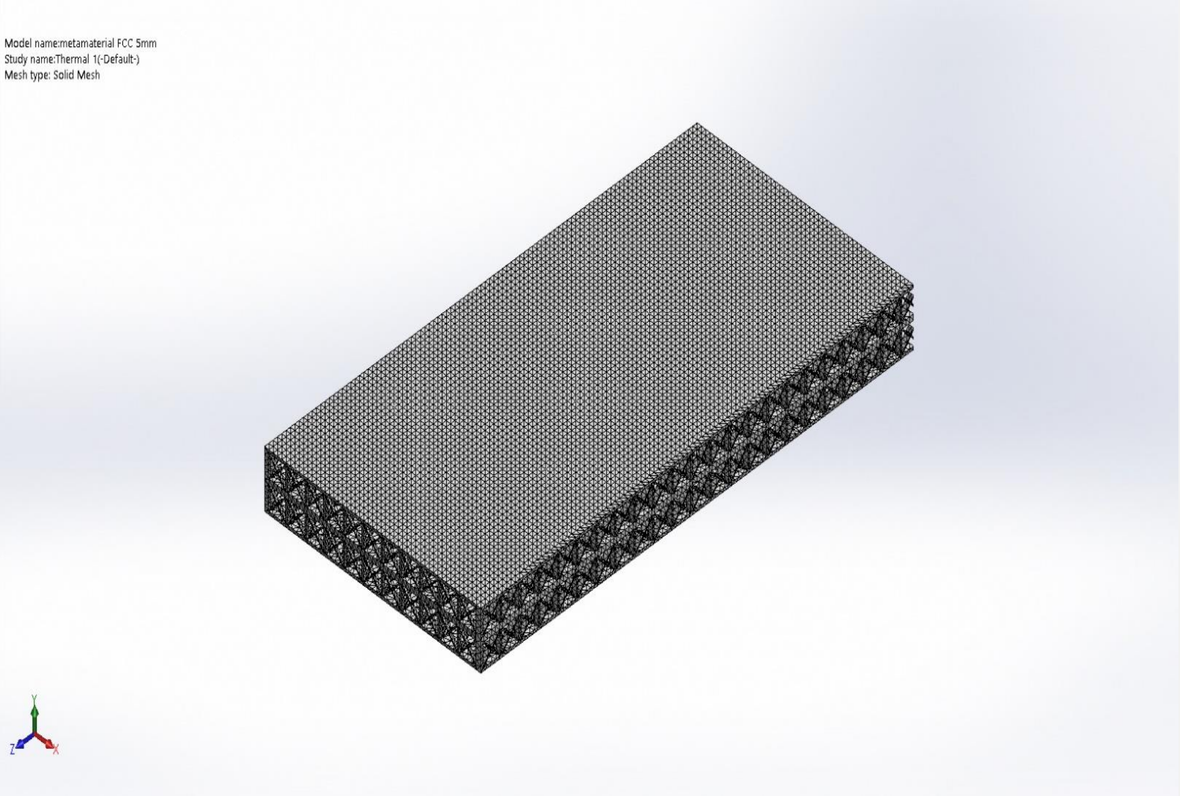


Fig 6.2 Meshed Model

Table 6.6 Meshed Model

6.7 STUDY RESULTS

Name	Type	Min	Max
Thermal1	TEMP: Temperature	27.931 Celsius Node: 4778	119.892 Celsius Node: 66778

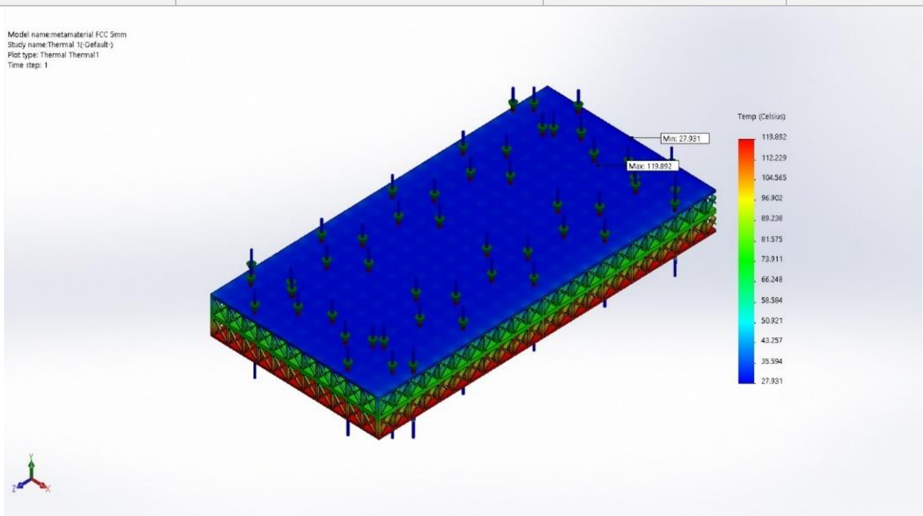


Fig 6.3 Study Results

metamaterial FCC 5mm-Thermal 1-Thermal-Thermal1

Table 6.7 Study Results

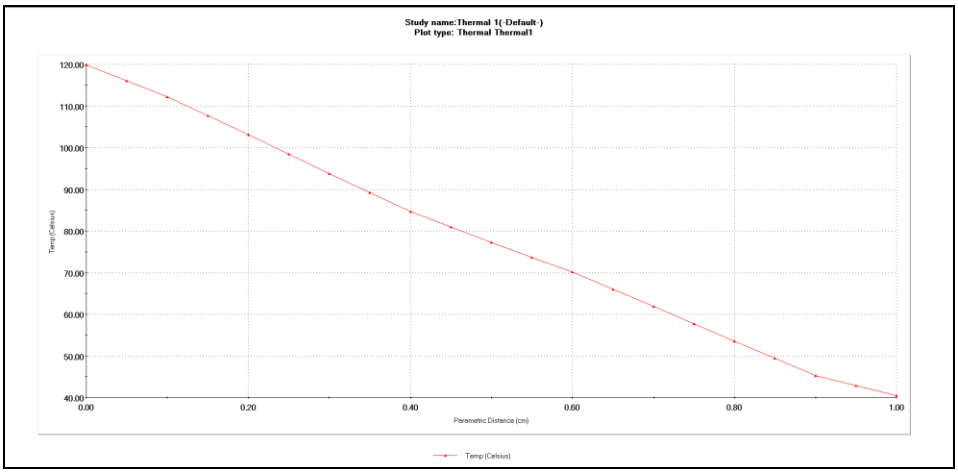


Fig 6.4 Temperature variation along length when used as insulator

CHAPTER-VII

CONCLUSION

We performed **TEMPERATURE ANALYSIS** by giving heat power input of 60W at bottom surface at a temperature of 100ºC and convectional heat transfer at top surface with a heat transfer coefficient of $80W/m^{2}$ -K. the side of the sample are completely enclosed. Based on the Temperature Analysis we can say that the material can provide a insulation up to a range of 40ºC - 50ºC. So, we can construct a duct for exhaust in air-conditioning systems. The ducts constructed by this metamaterial will provide best insulation that the conventional ducts used till date.

We performed the **FLOW ANALYSIS** by sending hot fluid between the top surface and bottom surface by enclosing the sides. Based on the flow analysis results we can say that we achieved an exchanging effect of 1ºC for 1cm of length of heat exchanger. So, we can construct the condensers for refrigeration system. The conventional condensers are non-reusable and recyclable but the condensers constructed using this metamaterial are reusable, recyclable and easy to manufacture.

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