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Vacuum Chamber Design for Advanced OLED Electronic Measurements

Materials Engineering /Faculty of Technology

Master's thesis

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Abstract.

Organic Light-Emitting Diodes (OLEDs) have emerged as a revolutionary technology in the field of optoelectronics. This work comprehensively examines OLEDs, encompassing their fundamental principle, device architecture, operational mechanics, common challenges, and encapsulation strategies. This research elucidates the unique capabilities and potential applications of OLED technology by delving into the underlying physics governing OLED operation, including electroluminescence and charge carrier dynamics. An in-depth analysis of OLED degradation sheds light on the diverse factors contributing to device performance decline over time, emphasizing the significance of robust encapsulation techniques and meticulous design considerations. The dynamics of pressure distribution within an OLED vacuum chamber are investigated through computational fluid dynamics (CFD) simulations and detailed design methodologies, highlighting the critical role of precise pressure control in optimizing device fabrication processes. Furthermore, the integration of System Operation Aeres for process automation within the OLED vacuum chamber showcases the potential for enhanced efficiency and reliability in OLED vacuum chamber design.

Future research endeavors are directed toward refining encapsulation techniques, advancing material science, and exploring emerging applications for OLED technology.

Keywords: OLEDs, OLED vacuum chamber, Design, CFD

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Disclaimer

This thesis used AI tools only to verify information and enhance knowledge. The AI tools assisted in verifying facts and ensuring information accuracy. No data is directly copied from AI-generated content in this thesis. All the ideas and conclusions presented in this thesis are original.

1 Abbreviations

OLEDs: Organic Light-Emitting Diodes

LCDs: Liquid-crystal display

CFD: Computational Fluid Dynamics

Aeres: System Operation Aeres

PVD: Physical Vapor Deposition

OPVs: Organic Photovoltaics

ITO: Indium Tin Oxide

OTFT: Organic Thin-Film Transistor

Vscan: Scan Voltage

Cst: Storage Capacitor

SW OTFT: Switching Organic Thin-Film Transistor

DR OTFT: Driving Organic Thin-Film Transistor

TADF: Thermally Activated Delayed Fluorescence

2 Introduction

In recent years, significant strides have been made in the field of optoelectronics, driven by the increasing demand for high-performance and long-lasting optoelectronic devices. These devices play critical roles in various sectors, including the internet, optical communication, displays, and photovoltaic applications, shaping our daily lives. Among the myriad of optoelectronic technologies, organic-semiconductor devices have emerged as particularly promising, leveraging the unique advantages offered by organic materials. These advantages include flexibility, low material cost, simple, scalable processing, and suitability (Lu et al., 2021;Salehi et al., 2019).

Physical Vapor Deposition (PVD) is a widely employed technique for depositing thin films in OLED manufacturing. PVD involves the physical transfer of material from a solid source to the substrate in a vacuum environment, resulting in the formation of thin films with precise control over thickness and composition. One of the notable advantages of PVD is its ability to deposit materials at relatively low temperatures, which is crucial for preserving the integrity of organic layers in OLED devices. In the fabrication of OLED using PVD, several vital steps ensure the precise deposition of organic thin films onto substrates (Bauri et al., 2021). Initially, the substrate, typically composed of glass or plastic and coated with transparent conductive layers like Indium Tin Oxides (ITO), undergoes meticulous cleaning to eliminate any contaminates that could impede film deposition. Subsequently, the substrate is placed within a vacuum chamber, where the pressure is reduced to create a high-vacuum environment. This step is crucial in minimizing impurities formation and ensuring uniform film deposition across the substrate surface (Utochnikova et al., 2012; Yamashita et al., 2001).

Organic materials, comprising host and guest molecules essential for OLED functionality, are heated to their evaporation temperatures within the vacuum chamber. As these materials evaporate, they travel directly to the substrate and condense onto its surface, forming thin films layer by layer. Control over the deposition rate and duration is paramount to achieve the desired film thickness. Real-time monitoring techniques such as quartz crystal microbalances or in-situ spectroscopic ellipsometry are often employed to ensure uniform film growth and precise control over the deposition process. OLEDs typically comprise multiple organic layers with distinct functions, including hole transport, electron transport, and emission layers. PVD facilitates the precise deposition of each layer, enabling the design and fabrication of complex device architectures tailored to specific performance requirements

(Utochnikova etal., 2012; Yamashita et al., 2001).

Low-temperature PVD offers significant advantages in OLED manufacturing. Firstly, it preserves the integrity of organic materials by mitigating the risk of thermal degradation associated with high temperatures. This preservation enhances device performance and longevity. Additionally, low-temperature deposition processes are indispensable for fabricating OLEDs on flexible substrates such as plastic, paving the way for developing bendable and rollable displays. Moreover, operating at lower temperatures reduces energy consumption during manufacturing, contributing to overall cost savings and environmental sustainability. Thus, utilizing low-temperature PVD techniques represents a critical advancement in OLED manufacturing, offering enhanced performance, flexibility, and sustainability (Utochnikova et al., 2012; Yamashita et al., 2001).

OLED devices fabricated through thermal evaporation or solution-process deposition face distinct challenges and advantages. While thermal evaporation enables precise layer control, its high material wastage renders it costly. Conversely, despite being cost-effective and suitable for mass production, the solution-process approach encounters hurdles such as solvent solubility issues and layer blending defects. Efforts to enhance solution-processed OLED quality, exemplified by Cynora GmbH's modular emitter system, aim to mitigate these challenges (Jou et al., 2017). Market demand favors portable, eco-friendly, cost-effective products, driving OLED adoption. With notable efficiency achievements surpassing traditional lighting sources, OLEDs offer customizable design, lightweight construction, and superior brightness levels. As conventional lighting grapples with efficiency and environmental concerns, OLED technology emerges as a compelling contender in the lighting sector (Jou et al., 2015).

OLEDs are highly sensitive to environmental factors, which can significantly impact their performance and longevity. Understanding the physics behind OLED degradation and the necessity of a vacuum chamber for fabrication is essential for optimizing device stability and functionality. OLED degradation involves several internal processes, including chemical reactions and morphological changes such as face alterations, crystallization, etc. Typically, degradation results in a gradual decline in device efficiency, often observed as a decrease in brightness under constant current or voltage conditions.

Consequently, luminance behavior over time within a fixed or predefined physical environment is the primary parameter to assess OLED lifetime. This duration is referred to as the device's lifetime, denoted as LT50 or T1/2, presenting the time it takes for luminance to half its fitness at a constant current density. Alternatively, more stringent matrices, such as LT70 and LT97, may be utilized, indicating the time it takes for luminosity to drop to 70% and 97% of its initial value, respectively. The latter metric holds particular significance in display manufacturing, as it corresponds to the threshold at which differences in brightness between adjacent display elements become perceptible. Some studies opt for constant voltage sources to assess device lifetime, which often accelerates luminance degradation compared to constant current-based aging tests. This acceleration is attributed to the concurrent increase in device impedance over time, leading to a further reduction in current density (Scholzet al., 2015).

One of the primary degradation pathways in OLEDs is the oxidation of organic materials, particularly the electron transport and emitting layers. Oxygen molecules infiltrate the device structure through defects or imperfections in the encapsulation layers or via diffusion through the substrate and electron materials. Upon exposure to oxygen, organic molecules undergo oxidation reactions, forming non-radiative defects, decreased charge carriers' mobility, and reduced luminescence efficiency. This degradation ultimately decreases the device's lifetime and performance (Kwon et al., 2019). Similarly, moisture can degrade OLED performance by inducing reactions that degrade organic materials and promote the formation of non-conductive or insulating layers through encapsulation layers and diffusion into the OLED stack, which reacts with organic materials, leading to hydrolysis and chemical breakdown. This moisture-induced degradation results in increased leakage currents, reduced luminance, and color shifts, ultimately compromising device reliability and functionality (Xu etal., 2004).

3 Theory

3.1 LEDs

LEDs are the most used color display products in the market. LEDs have different advantages over conventional cathode ray tubes (CRTs), such as their low weight, low energy consumption, and higher brightness. Additionally, LEDs have a relatively longer life expectancy, in addition to their durability and small size. Moreover, LEDs have a higher light output to energy input ratio than incandescent bulbs and are more energy efficient. A conventional light-emitting diode (LED) consists of two types of semiconductors bonded together and attached to positive and negative electrodes. Generally, a semiconductor is a material with varying conductivity. Usually, semiconductors are poor conductors of electricity, but when doped (addition of impurities) to allow electrons to flow more freely, they become excellent conductors.

In LEDs, the negative electrode is attached to an N-type semiconductor (surplus of electrons), and the positive electrode is connected to a P-type semiconductor (surplus of positively charged particles). The electrons flow freely when the circuit is complete and fall from the conducting band into a lower orbital. As a result, energy is released in the form of photons, and a specific light color is produced depending on the photon's wavelength. The wavelength of the photon depends on the band gap. The lower wavelength photons (~350 - 450nm) lie in the purple-blue range of the spectrum. The photons with higher wavelengths (~650-700nm) are in the red range. In LEDs, the composition of semiconductor materials determines the color of light emitted, and a range of inorganic materials are used as semiconductors for this purpose.

The workings of OLEDs are primarily similar to those of LEDs, except that the P-type and N-type semiconductors are made of organic materials. This ensures the safe production and disposal of these devices. Polymers like polyfluorene make N-type materials, while P-type materials are made from polymers like polyaniline. In OLEDs, polymers used as semiconductors are doped for more effortless electron transfer. The structure of an OLED consists of a substrate, the anode layer, the conductive layer, the emissive layer, and the cathode.

3.2 OLED

The abbreviation 'OLED' represents an Organic Light-Emitting Diode, a technology utilizing LEDs where illumination arises from organic molecules. These organic LEDs are pivotal in crafting what is widely acknowledged as a superior display globally (Tsujimura, 2017). OLEDs are solid-state devices of thin organic films between two conductive electrodes. Upon the application of electricity, charge carriers move from the electrodes into the organic layers, forming excitons in the emissive zone, which then emit light. The OLED cell structure includes a substrate (plastic, glass, or metal foil), an anode (positively charged to inject holes into the organic layers), a hole injector layer (receives holes from the anode), a hole transport layer (facilitates hole transport), an electron transport layer (facilitating electron transport), a blocking layer (improving OLED technology), an electron transport layer(facilitating electron transport), and a cathode (negatively charged to inject electrons). Each layer plays a crucial role in the functioning of OLED devices, converting electrical energy into light efficiently (Lu et al., 2018; Patel & Prajapati, 2014). The active area or pixels are the regions where light emission occurs, enabling the display of images or content. These active areas consist of multiple organic layers with distinct functions, including hole transport, electron transport, and emissions layers. Figure 1 illustrates the cross-section of an OLED device; electrons and holes are injected into the organic layers, where they recombine at the emissive layer interface. This recombination process leads to the formation of excitons, which subsequently decay to emit photons. The emission wavelength and intensity are determined by the properties of the organic materials used in the device. By controlling the design and composition of the active areas, OLED manufacturers can optimize device performance, achieving high brightness, color accuracy, and energy efficiency (Kim & Song, 2019). Figure 1 outlines the structure and functionality of a standard pixel circuit employed in OLED panels. This circuit comprises two organic thin-film transistors (OTFTs), one OLED, and one capacitor. The switching OTFT (SW OTFT) is activated by a scan voltage (Vscan) to transfer data from the data line to the storage capacitor (Cst). Its primary role is to provide a substantial current to rapidly charge the capacitor during scanning while maintaining a low off-state current to sustain capacitor voltage. The driving OTFT (DR OTFT) is subsequently triggered by the stored voltage in the capacitor to supply a large current to the OLED, ensuring bright illumination (Kim & Song, 2019).

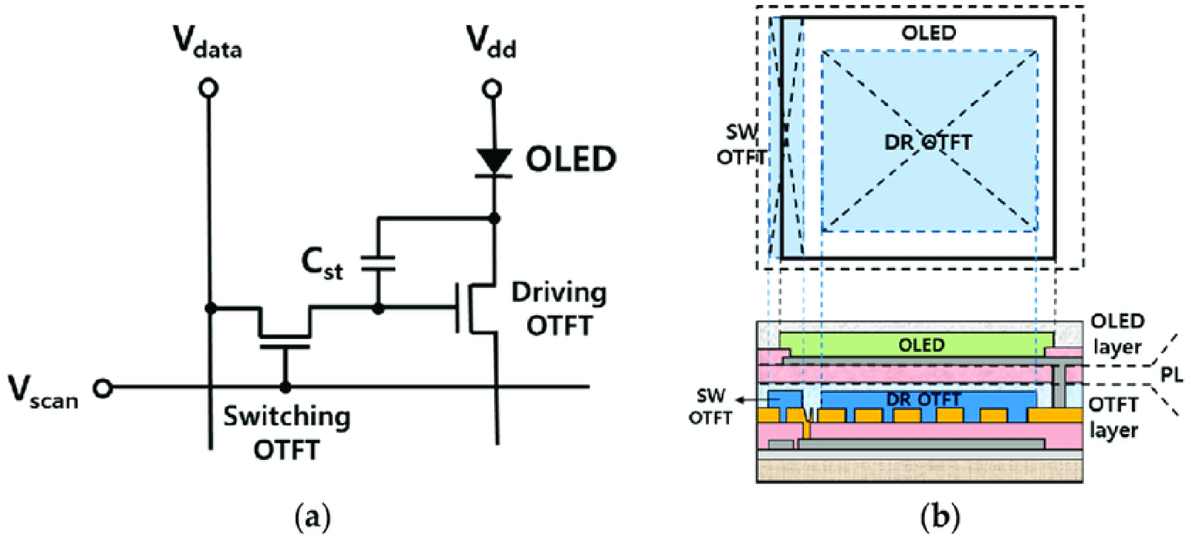

Figure 1: Active areas or pixels in OLED (a) shows the pixel circuit in the OLED panel. It comprises two organic thin-film transistors (OTFT), one OLED, and one capacitor. (b) shows the layout and the cross-sectional view of the stacked pixel with all the components (copyright, Kim & Song, 2019)

OLED materials are employed in constructing thin films positioned between dual conductors. Upon application of electrical current, they emit vibrant light. This straightforward configuration yields numerous advantages over alternative display technologies. OLEDs facilitate emissive display, wherein each pixel is independently controlled and emits its light, distinct from LCDs relying on a backlighting unit. OLED displays boast exceptional image quality, characterized by vivid colors, seamless motion, and, notably, unparalleled contrast, including true black, which is unattainable in LCDs due to backlighting. Furthermore, the uncomplicated OLED design lends itself to the relatively straightforward production of flexible and transparent displays (Mandle, 2010; Tsujimura, 2017).

OLED materials are integral components between dual conductors, typically an anode and a cathode. These materials emit vibrant light upon applying electrical current, forming the basis of an OLED display. One key advantage of OLEDs is their emissive display nature, wherein each pixel functions independently, emitting light. This contrasts with LCDs, which rely on a backlighting unit, leading to contrast and color accuracy limitations. OLED displays excel in image quality, offering vivid colors, seamless motion, and unparalleled contrast, including accurate black levels unachievable in LCDs. Additionally, the straightforward design of OLEDs facilitates the production of flexible and transparent displays, expanding their versatility in various applications.

In constructing OLEDs, attaching cathodes and anodes to the active area is crucial for device functionality. Typically, the anode is placed on the substrate side, while the cathode is on the opposite side. This configuration allows efficient electron injection from the cathode and hole injection from the anode into the organic layers, promoting balanced charge transport and recombination within the active area. The precise arrangement of cathodes and anodes can be illustrated through diagrams depicting the layered structure of OLED devices, emphasizing the strategic placement of electrodes to ensure optimal device performance and functionality.

3.3 OLED Device Structure

The fundamental structure of OLEDs is straightforward: an organic emitter sandwiched between two electrodes. However, commercial OLEDs incorporate intermediary layers, such as electron transport and blocking, to develop efficient and durable devices. The entire organic stack is between the electrodes and deposited onto the substrate (either glass or plastic) and the display backplane (housing driver electronics). Specific OLED displays available today utilize numerous layers stacked atop one another to achieve the desired performance and functionality (Negi et al., 2018; Salehi et al., 2019).

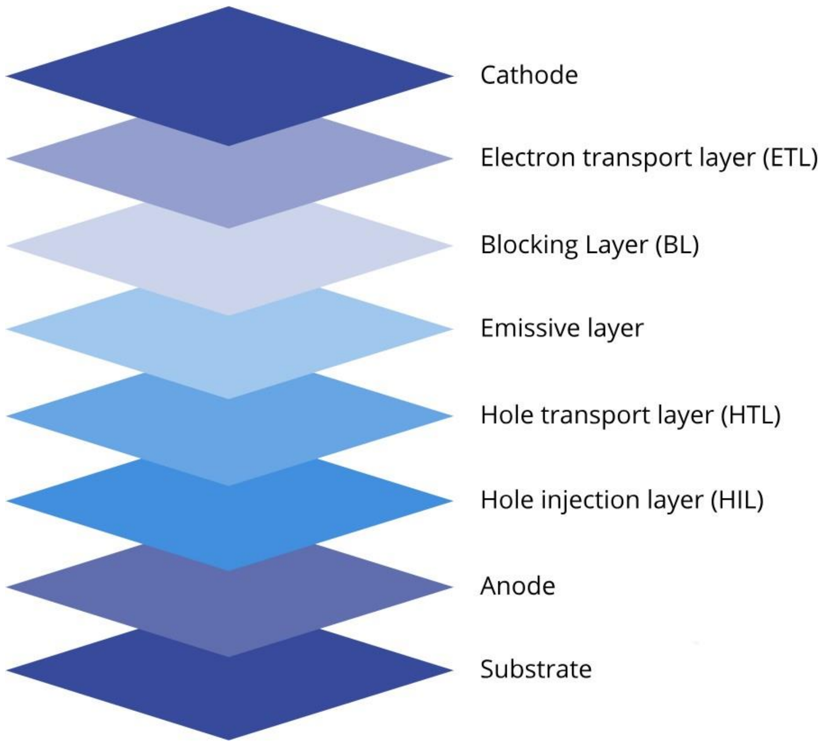

Figure 2: The basic structure of an OLED, including the different layers involved in its functioning. There are multiple layers between the cathode and the anode, and are stacked on the substrate.

The layers shown in the image include the hole injection layer (HIL), hole transport layer (HTL), emissive layer, blocking layer (BL), and electron transport layer (ETL). These intermediate layers are used to develop efficient and durable devices.

Figure 2 shows the basic structure of an OLED. The different layers involved in the structure are utilized to develop efficient devices. These layers also increase the longevity of these OLED devices.

3.4 OLED Mechanism

The working of Organic Light light-emitting diodes (OLEDs) is almost like LEDs; however, the emissive and conductive layers are made from organic materials. The materials must be organic to manufacture and dispose of the devices safely. Polymers like polyfluorene help create emissive layers, while polymers like polyaniline help create conductive layers.

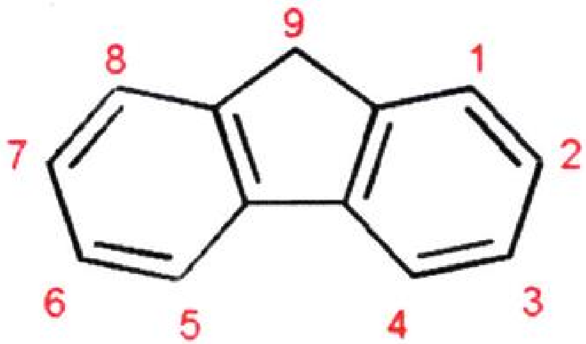

Figure 3: Structure of polyfluorene. Fluorine units are linked in linear chains. Positions 2 and 7 are the fluorine-connected molecules in polyfluorene. Position 9, as shown in this structure, is the point in the polyfluorene structure where side chains are attached, forming a linear chain.

Since these compounds have phenyl groups that help stabilize radicals, they are excellent semiconductor choices. This is because the electron clouds can mesh because of the alignment of the pi-orbitals in the double bond, which are resonant with two different conformations.

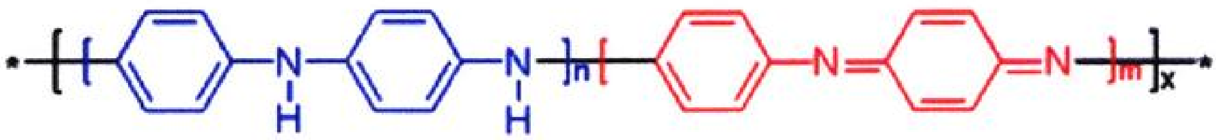

Figure 4: This is how polyaniline is structured. In this diagram, the number of units in the chain (degree of polymerization) is represented by x, and n+m - l—

As a result, the pi-bond can stabilize the free radical when the N-type material loses an electron and becomes unstable due to the presence of a free radical in the molecule by sharing the excess negative charge among all the pi-bonds that have been meshed. This also applies to the P-type material that is receiving electrons. The phenyl groups' pi-bond can stabilize electrons taken in as free radicals.

The polymers used as OLED semiconductors need to be doped to facilitate more accessible electron transport, like semiconductors in LEDs. Doping a polymer can be done in two ways. In the first method, a polymer is subjected to an oxidant or a reduction agent. This will result in a polymer doped with more electrons to form an N-type or fewer electrons to form a P-type. Polymers are doped using an electrochemical reaction in the second method. In this procedure, a polymer-coated electrode is submerged in an electrolyte solution in which the polymer is insoluble. Additional reference electrodes should be included in the solution. Ions from the electrolytes and a charge are produced when current flows through the solution; for an N-type doped polymer, this additional charge results in the addition of electrons, and for a P-type doped polymer, it results in the removal of electrons.

The substrate, or the material that supports the system, is the first component of a typical OLED's construction. The material in question typically resembles a glass or silicon slide. The anode layer sits on top of this and removes electrons from the P-type material when current flows through it. The emissive layer comes next in the OLED, followed by the conductive layer. Lastly, a cathode layer is added, as seen in Figure 2.

3.5 OLED Problems

One of the critical components in the manufacturing process of OLEDs is the vacuum chamber, which plays a pivotal role in depositing organic materials onto the substrate to create thin organic layers (Porada, 2019). Maintaining a vacuum within the chamber is critical for preventing contamination and ensuring the quality of the deposited organic layers. Any impurities or foreign particles can significantly impact the performance and lifespan of an OLED device. As a result, leaks or breaches in the vacuum chamber can reduce production yields and product quality (Sun et al., 2020). Furthermore, achieving and maintaining the desired vacuum level necessitates sophisticated equipment and accurate control systems. Even minor pressure fluctuations can cause inconsistencies in the thickness and uniformity of the organic layers, resulting in differences in the optical and electrical properties of OLEDs. This can result in color shifts, luminance variations, and decreased efficiency (Kreiza et al., 2021).

Additionally, the vacuum chamber experiences deterioration over time, particularly from exposure to deposition procedures, high temperatures, and reactive gases. Degradation of components like pumps, vacuum chambers, and seals can lead to more frequent maintenance needs and repair downtime (Fujimoto et al., 2018). One more challenge related to the vacuum chamber is the actual deposition procedure. Precise adjustment of deposition rates, pressure, and temperature is necessary to control the organic layer thickness, uniformity, and deposition rate. Deviations from the ideal conditions may result in non-uniform convergence, pinholes, and grain boundaries, among other defects, which may impair the dependability and performance of the device.

3.6 OLED Degradation

OLED degradation refers to the gradual deterioration of OLED device performance overtime. Several factors contribute to OLED degradation (Popovic & Aziz, 2002; Scholz et al., 2015). Organic material degradation is the fundamental problem that OLEDs face. Exposure to light, moisture, and oxygen in the environment can cause organic materials used in OLEDs to deteriorate (Scholz et al., 2015). Operational stresses are the second most common reason for OLED degradation. The electrical current must pass through an OLED to function, which may stress the organic layers (Alchaddoud et al., 2018). The temperature effects are the third most common degradation method. High temperatures can cause acceleration in OLED deterioration processes when the device is operating or due to external factors (Alchaddoud et al., 2018; Scholz et al., 2015). The quality of encapsulation is another major factor in the degradation of OLEDs. When OLED devices are not adequately encapsulated, moisture and oxygen can seep into the organic layers, causing chemical deterioration and eventual device failure (Kalyani & Dhoble, 2015). According to (Fujimoto etal., 2018), optimizing design and fabrication, material selection, and device architecture can reduce degradation effects and increase device reliability.

The vacuum level significantly influences the degradation of OLEDs both during the fabrication and the operational stage. During the fabrication stage, it is critical to maintain a high vacuum level (in the range of $10^{-7} – 10^{-6}$ Torr) to prevent contamination. Small amounts of contaminants like air and moisture can accelerate degradation. Maintaining high vacuum levels is necessary to ensure the uniform deposition of organic and metal layers. Poor vacuum conditions result in non-uniform deposition, leading to localized electric stress and device failure. A high vacuum level is maintained to ensure that the evaporating molecules travel directly to the substrate and spread out evenly and uniformly on the surface to create thin films. The techniques generally employed for material deposition are thermal evaporation and sputtering. These techniques require high vacuum conditions. During the operational phase, if the vacuum level is lower (higher pressure), oxygen and moisture can be introduced, leading to oxidation and hydrolysis of calcium and aluminum. These chemical reactions can result in the degradation of organic layers. The effectiveness of the encapsulation of OLEDs also partly depends on the vacuum level during sealing. In case of poor vacuum conditions, residual gases get entrapped in the encapsulation. Keeping high vacuum levels during the operational phase is critical in maintaining the stability of organic molecules in OLEDs and preserving the integrity of interfaces between different layers in OLEDs.

There are two layers of interfaces in the OLEDs. First is the interface between the organic layer and metal cathode required for efficient charge injection. Second is the interface between different organic layers. If there are poor vacuum conditions, interfacial oxides can be formed, resulting in degradation of contact quality and reduced efficiency.

During the OLED operation at elevated temperatures, volatile substances trapped during fabrication can be released. If vacuum levels are not high enough, these substances can redeposit on the OLED surfaces, leading to non-uniformities and degradation.

3.7 OLED Encapsulations

In OLED technology, encapsulation is of primary importance. The purpose of encapsulation is to prevent the degradation of the organic layers of OLEDs. Oxygen and moisture can result in the degradation of these organic layers, making OLED devices less durable (Jeong et al., 2020; Shin, 2018). In encapsulation, barrier films and coatings protect against the entry of moisture and oxygen. These protective films use metal oxides like aluminum oxide and silicon oxide, polymers, or hybrid organic or inorganic materials. These materials have enhanced barrier properties (Jeong et al., 2020). Some encapsulation techniques employed are thin film encapsulation, atomic layer encapsulation, plasma-enhanced chemical vapor deposition, and organic or inorganic hybrid encapsulation. In OLED manufacturing processes, each technique exhibits different levels of barrier performance, scalability, and compatibility (Fujimoto et al., 2016; Kalyani & Dhoble, 2015).

In flexible OLEDs, traditional glass substrates are not suitable for use, which makes encapsulation challenging. Flexible encapsulation solutions are required for flexible materials like plastic and metal foil that can endure stretching and bending without compromising barrier properties (Jeon et al., 2022). Encapsulation technology is advancing rapidly. Nevertheless, there are still some challenges that need more research and development. One of these challenges is to find ways to ensure the cost-effectiveness and long-term stability of the encapsulations. The current encapsulation manufacturing techniques are not cost-friendly, making high-volume manufacturing expensive. Due to these challenges, manufacturing encapsulations on a large scale is complex, thus hampering improved performance and compatibility (Shin, 2018). In industry, rigorous testing is performed to evaluate the efficiency and effectiveness of encapsulation methods and the materials used for manufacturing. These tests include accelerated aging tests, environmental exposure tests, and barrier property measurements. These tests ensure the encapsulated OLEDs perform best and are reliable under different conditions (Kalyani& Dhoble, 2015).

3.8 OLED Vacuum Chamber Material

The vacuum chamber utilized in OLED fabrication plays a critical role in maintaining a controlled environment free from contaminants such as moisture and oxygen; aluminum is commonly chosen for constructing the vacuum chamber due to its advantageousproperties. Aluminum offers excellent vacuum sealing capabilities, high thermal conductivity, and corrosion resistance, making it ideal for maintaining a stable vacuum environment during OLED fabrication. Additionally, aluminum is relatively lightweight and cost-effective compared to alternative materials such as stainless steel or glass. These characteristics ensure efficient operation and longevity of the vacuum chamber, contributing to the high-quality fabrication of OLED devices (Nakhosteen & Jousten, 2016).

Borosilicate glass is often preferred for the transparent glass material used in the vacuum chamber of OLED fabrication due to its favorable properties. Borosilicate glass offers excellent transparency, allowing for visual monitoring of processes inside the chamber. It also exhibits high chemical resistance, preventing reactions with substances in the chamber environment. Additionally, borosilicate glass has a low thermal expansion, ensuring dimensional stability under varying temperatures during OLED fabrication. These characteristics make borosilicate glass suitable for maintaining a controlled environment within the vacuum chamber, facilitating efficient OLED manufacturing processes (Melpignano et al., 2010).

Materials with high electrical conductivity and corrosion resistance are essential for the electrical wires used in the vacuum chamber of OLED characterization. Copper is commonly chosen for this purpose due to its excellent electrical conductivity, allowing for efficient transmission of electrical signals within the chamber. Additionally, copper exhibits good resistance to corrosion, ensuring the long-term reliability of the electrical connections even in a vacuum environment. The use of copper wires helps maintain stable electrical performance during OLED characterization processes, contributing to the overall efficiency and quality of OLED devices (Wang et al., 2019).

3.9 OLED Emitters

OLED emitters play a crucial role in determining the performance and characteristics ofOLED devices. Over the years, significant advancements have been made in OLED emitter technology, leading to the development of different generations of emitters: fluorescence (first. Generation), phosphorescence (second generation), and thermally activated delayed fluorescence (third generation), as seen in Table 1.

3.8.1 Fluorescence Emitters

Fluorescent OLED emitters were among the earliest types used in OLED technology. These emitters operate based on the principle of fluorescence, where the excited state energy isreleased as light. Fluorescent emitters are typically composed of organic molecules that emit light when excited by an electric current. While fluorescence emitters have been instrumental in the early development of OLEDs, their relatively low efficiency and limited color options have spurred the exploration of more advanced emitter technologies (Hong et al., 2021).

3.8.2 Phosphorescence Emitters

Phosphorescence OLED emitters represent a significant advancement over their fluorescent counterparts, particularly in efficiency. Phosphorescence exploits the phenomenon of spin-orbit coupling, allowing for efficient harvesting of both singlet and triplet excitons. This enables phosphorescent emitters to achieve higher internal quantum efficiencies,leading to brighter, more energy-efficient OLED devices. Additionally, phosphorescent emitters offer a broader range of colors and enhanced stability than fluorescent emitters,making them highly desirable for various applications, including displays and lighting (Kappaunet al., 2008).

Generation	Emission Type	Color Availability	Efficiency	Cost
1st	Fluorescence	Deep Blue	Low	Low
2nd	Phosphorescence	Green, Red (Not Blue)	High	High
3rd (TADF)	Thermally Activated Delayed Fluorescence	Under development for Deep Blue (Expected)	High (Expected)	Low (Expected)

Table 1: OLED generations. The emission types, color availability, efficiency, and costs of 1st, 2nd, and 3rd generations. The 1st generation OLEDs have fluorescent emitters, 2nd generation have phosphorescence emitters, and 3rd generation OLEDs have thermally activated delayed fluorescent emitters. The color available for 1st generation OLEDs is deep blue, and they have low cost and low efficiency. 2nd generation OLEDs are available in green and red color and have high costs and high efficiency. 3rd generation OLEDs are under development due to the availability of deep blue color. Their efficiency and cost are expected to be high.

Table 1 shows the development of different generations of emitters. Fluorescence (first generation), phosphorescence (second generation), and thermally activated delayed fluorescence (third generation). It also shows the color availability efficiency and cost of these generations of emitters.

3.8.3 Thermally Activated Delayed Fluorescence (TADF) Emitters

TADF emitters represent the latest frontier in OLED emitter technology, offering the potential for further improvements in efficiency and performance. TADF emitters utilize a unique mechanism where delayed fluorescence occurs by efficiently converting triplet exciton to singlet excitons via reverse intersystem crossing. This enables TADF emitters to achieve high internal quantum efficiencies comparable to phosphorescent emitters while utilizing only organic materials without heavy metal complexes. The development of TADF emitters has opened up new possibilities for achieving high-efficiency OLEDs with reduced manufacturing costs and improved sustainability (Im et al., 2017).

4 Methodology

The OLED vacuum chamber design and CFD simulation methodology follow the following order.

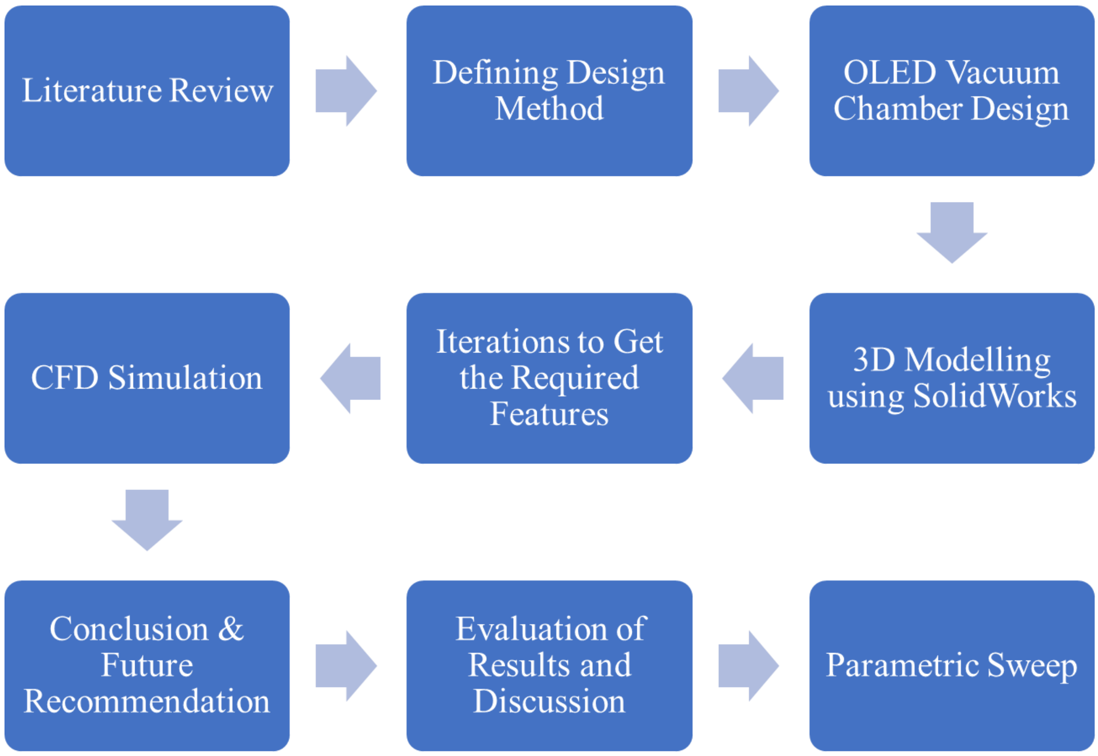

Figure 6: Flow chart for design and CFD simulation methodology. The methodology starts with a literature review, defining design method, OLED Vacuum chamber design, 3D Modelling using SolidWorks, Iterations to get the required features, CFD simulation, Conclusion and future recommendation, evaluation of results and discussion, and ends with a parametric sweep.

Figure 6 shows the flow chart for the methodology employed for the design and CFD simulation of the vacuum chamber. It starts with the literature review and ends with the parametric sweep to determine the effect of pressure variation on the vacuum creation in the chamber.

4.1 OLED Vacuum Chamber Design

A successful OLED vacuum chamber design must combine creative design with structured design methodology and computer-aided design tools. The method employed in the design of the vacuum chamber for the OLED is design methodology.

4.1.1 Design Methodology

Design methodology is defined as the work to find an innovative and reasonable solution according to the customer's requirement or meeting the requirements. The design methodology was chosen because of its flexibility, which helps develop a particular idea and apply improvements to the already available design in the most suitable way.

Additionally, employing design methodology ensures that the OLED vacuum chamber is innovative, practical, and aligns with the requirements. By iteratively refining designs and incorporating feedback, this approach enables the creation of a vacuum chamber that optimally balances functionality, efficiency, and manufacturability. Through computer-aided design tools, intricate details can be carefully analyzed and optimized, further enhancing the overall performance and reliability of the OLED vacuum chamber, as seen in Figure 7.

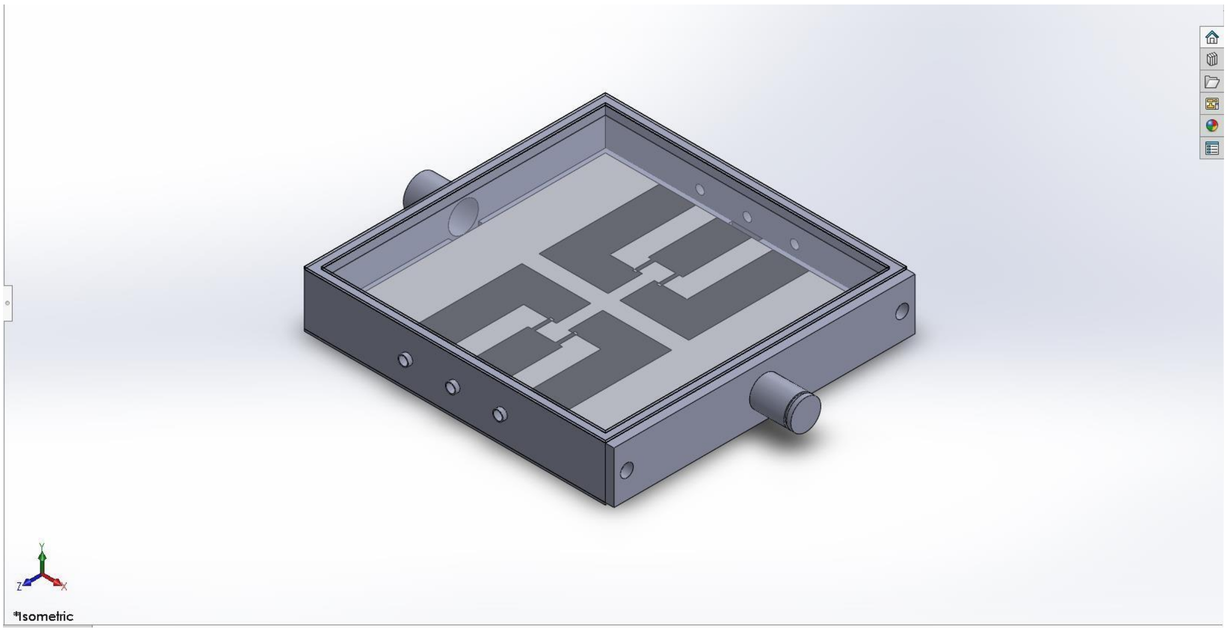

Figure 7: 3D CAD model of the OLED vacuum chamber and the OLED placed inside the chamber. The design is created after carefully analyzing and optimizing the intricate details.

Figure 7 shows the 3D CAD model of the OLED vacuum chamber and the OLED placed inside the chamber. The design is created using computer-aided design tools.

4.2 Design Details

SolidWorks Standard software is the design tool used for the 3D modeling of the OLED vacuum chamber. In the pursuit of designing OLED using SolidWorks, a thorough design methodology is paramount to ensure precision and efficiency. The process commences with creating a new part file within the SolidWorks interface, establishing the foundational platform for design exploration. Leveraging the sketch tools, the outline of the

OLED is carefully crafted, adhering regularly to the specific dimensions: 15 mm in length, 13 mm in width, and 1mm in height, as seen in Table 2. The dimensions are kept slight since the overall size of OLEDs is small. This initial sketch serves as the blueprint for subsequent design iterations. Subsequently, employing the Extrude Boss/Base feature, the sketched outline is extruded to precisely 1 mm in height, constituting the OLED substrate's base structure. Attention is precisely directed towards the addition of crucial components,

including electrode and organic layers, each imbued with exacting dimensions to ensure congruence with design specifications, as seen in Figure 8.

Table 2: Details of OLED dimensions

OLED Dimensions	
length	15 mm
width	13 mm
height	1 mm

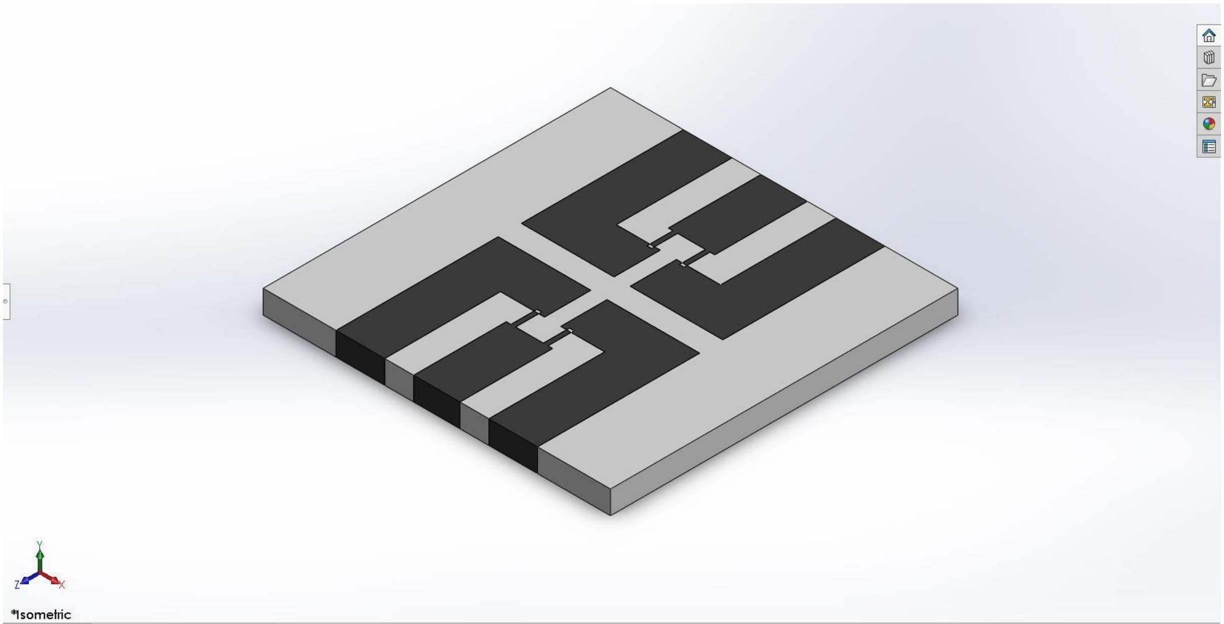

Figure 8:3D view of OLED for the OLED vacuum chamber. The dimensions are 15 mm long, 13 mm wide, and 1mm high. Extrude Boss/Base feature is used, and the sketched outline is extruded to a height of precisely 1 mm.

The base plate for the OLED vacuum chamber, with dimensions of 16.75 mm in length, 16.5 mm in width and 0.85 mm in height, prioritizes structural stability and functional capability. Each component, carefully arranged, ensures optimal device performance. Additionally, specific features such as an impression were designed on the bottom plate to ensure proper encapsulation of OLED when placed inside the vacuum chamber. The detailed model of the bottom plate of the OLED vacuum chamber is shown in Figure 9.

The base or bottom plate is fundamental to the OLED vacuum chamber. It serves as a foundation and is made of sturdy material. The base plate holds all the components in place to ensure proper functioning. The base plate is airtight to ensure that the vacuum is maintained. The plate is designed to align all the components mounted on it correctly. The plate design also ensures that there is no source of leakage or contamination.

Table 3: Details of vacuum chamber bottom lid dimensions

Vacuum Chamber Bottom Lid Dimensions	
Length	16.75 mm
Width	16.5 mm
Height	0.85 mm

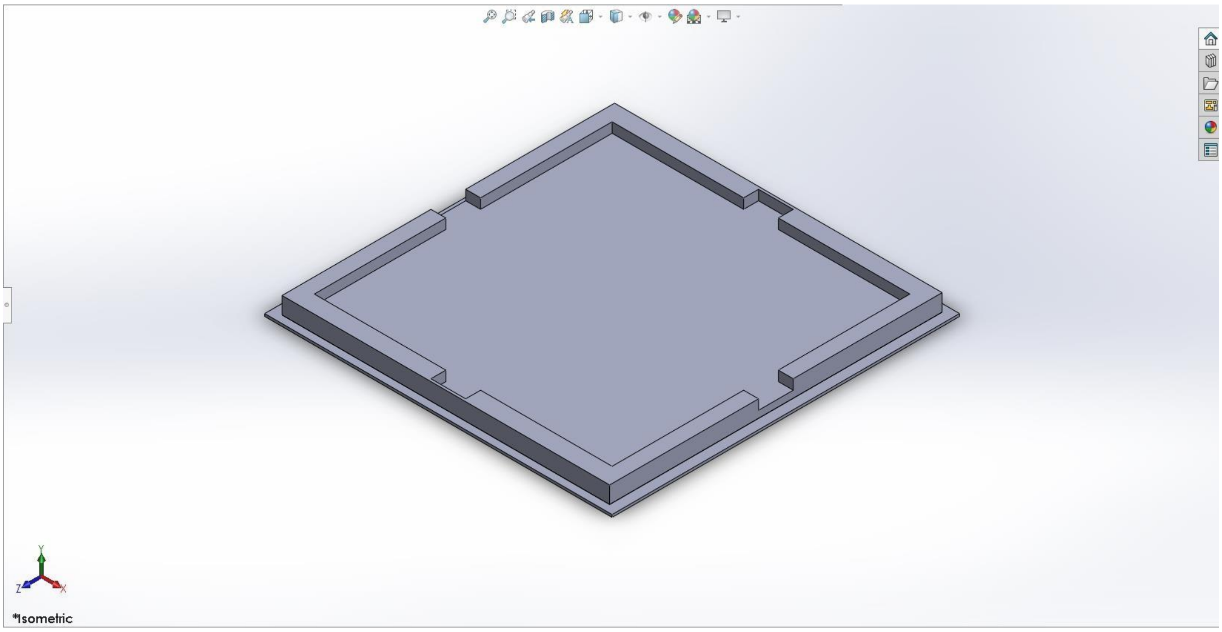

Figure 9: 3D view of the bottom plate for the OLED vacuum chamber. The dimensions are 16.75 mm in length, 16.5 mm in width, and 0.85 mm in height. Specific features such as an impression are used on the bottom plate to ensure proper encapsulation of OLED.

The top lid for the vacuum chamber, with dimensions 16.5 mm in length, 16.5 mm in width, and 0.5 mm in height, is designed for precise functionality and structural integrity. The top plate is kept transparent to ensure the electrical connections are made correctly, and the operation of the OLED and light generation mechanism can be observed and monitored accurately. Material selection and geometric configurations are carefully considered to ensure compatibility with the chamber's requirements. The detailed model of the top plate of the OLED vacuum chamber is shown in Figure 10.

The top plate or top lid is made of durable material. It is transparent so that all the processes inside the vacuum chamber can be observed while maintaining the vacuum. It serves as the upper boundary and is securely fastened. Transparency helps in monitoring the operations from outside without opening the vacuum chamber. The top lid is also perfectly sealed to maintain the vacuum inside. It is designed in such a way that it can withstand the pressure difference between inside and outside.

Table 4: Details of vacuum chamber top lid dimensions

Vacuum Chamber Top Lid Dimensions	
length	16.5 mm
width	16.5 mm
height	0.5 mm

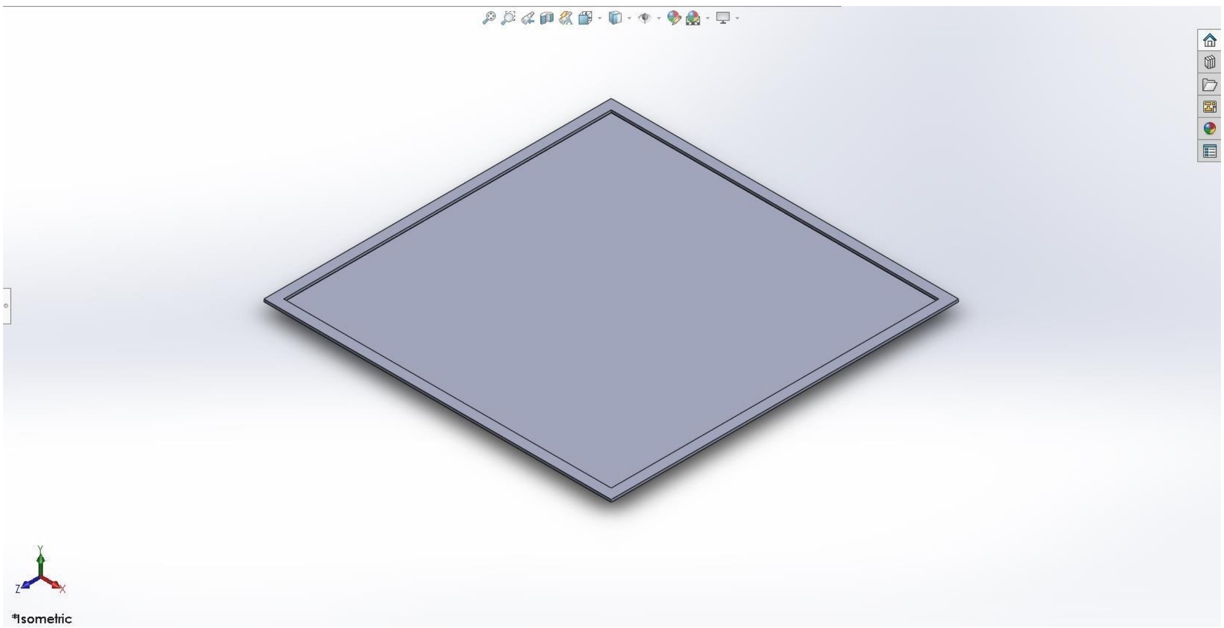

Figure 10: 3D view of the top plate/lid for the OLED vacuum chamber. The dimensions for the top plate are kept at 16.5 mm in length, 16.5 mm in width, and 0.5 mm in height.

The side enclosure for the OLED vacuum chamber has a length of 17.5 mm, a width of 17.5 mm, and a height of 3 mm. It is designed to ensure optimal functionality and compatibility. In addition to these dimensions, the enclosure features three side holes for electrical connections on both the left and right sides, facilitating seamless integration with external systems. Furthermore, a groove of 0.6 mm is incorporated for enhanced stability and mounting options. Additionally, a front open section measuring 15 mm in length and 1.5mm in width is included to facilitate the insertion of the OLED device into the vacuum chamber. Through thorough design and precision engineering, the side in the clear provides robust support and accessibility for the OLED vacuum chamber system, as seen in Figure 11.

One integral component of the OLED vacuum chamber is the side enclosure. It is carefully designed to ensure that connections and mounting requirements are entirely met. There are several functions of the side enclosure. It is a protective barrier, defining the chamber's internal space. It provides the required openings for the necessary electrical connections and device insertion. This design has three side holes for electrical connections on the left and right sides. These holes ensure that external systems are seamlessly integrated without affecting the vacuum inside. The groove is vital for maintaining stability and ensuring securing mounting. The design consists of a front opening section that facilitates the insertion of an OLED device. The accurately selected dimensions and the groove inclusion ensure that the vacuum is maintained in the chamber. The side holes are accurately sealed, and the enclosure fits tightly, so there is no risk of gaps. The front open section also maintains the vacuum integrity during the insertion of the OLED device.

Table 5: Details of vacuum chamber enclosure dimensions

Vacuum Chamber Enclosure Dimensions	
length	17.5 mm
width	17.5 mm
height	3 mm
Side Groves (left and right) in number	3 (each side)
Side Grove Dimensions	0.6 mm (diameter)
Front Open Section	15 mm by 1.5 mm
Back Grove	2 mm (diameter)

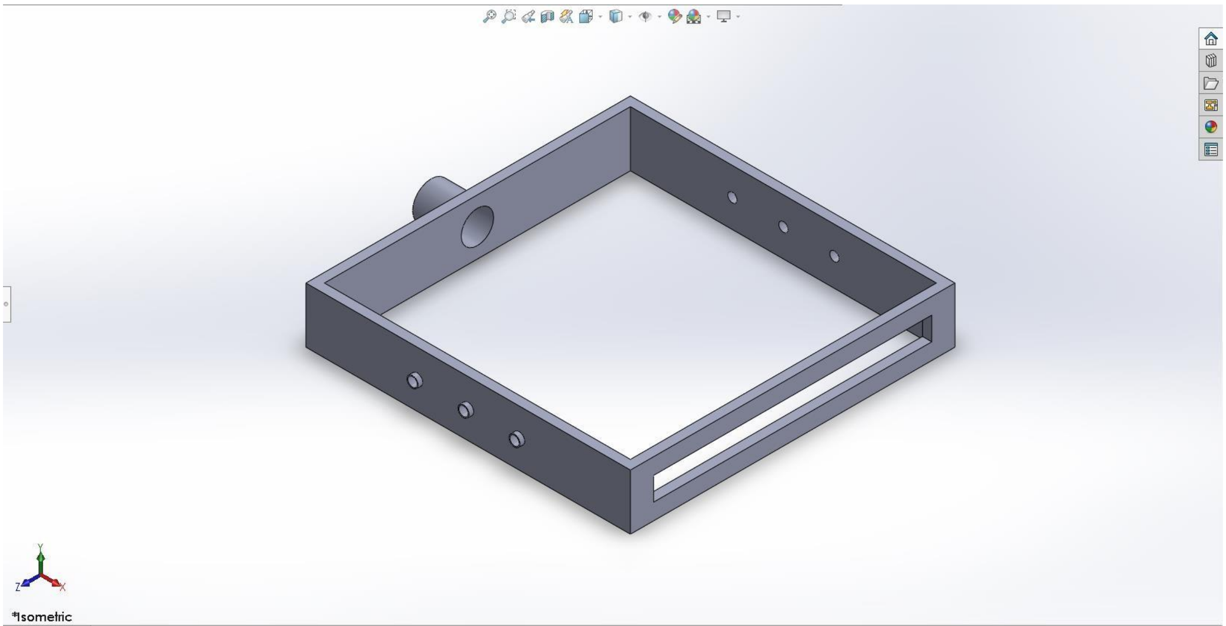

Figure 11: 3D view of the side enclosure for the OLED vacuum chamber. The side enclosure for the OLED vacuum chamber has a length of 17.5 mm, a width of 17.5 mm, and a height of 3 mm. A groove of 0.6 mm is incorporated for enhanced stability. A front open section measuring 15 mm in length and 1.5mm in width is included to facilitate the insertion of the OLED device.

The front closing strip for the Vacuum Chamber Top Lid, measuring 17.5 mm in length, 3 mm in width, and 0.5 mm in height, serves as a crucial component for sealing and securing the chamber. Featuring a single groove of 2 mm in depth, the closing strip provides a secure hold, ensuring the top lid remains firmly in place during operation. This grooved design facilitates effortless assembly and disassembly while maintaining an effective seal to preserve the vacuum environment inside the chamber, as seen in Figure 12.

Even though the front closing strip is a small component of the vacuum chamber, it is vital for proper functioning. It is designed to ensure the top lid is working accurately. It seals and secures the top lid and keeps it firmly in place during the operation. A groove in the front strip is essential to provide a tight fit and prevent movement during the operation. Due to this groove, the top lid can be easily assembled and disassembled. The front closing strip maintains the overall integrity of the vacuum chamber. The grooved design of the front closing strip provides secure sealing and prevents air leakage. This airtight seal ensures maintaining the vacuum.

Table 6: Details of vacuum chamber front closing strip dimensions

Vacuum Chamber Front Closing Strip Dimensions	
length	17.5 mm
width	3 mm

height	0.5 mm
Front Grove	2 mm

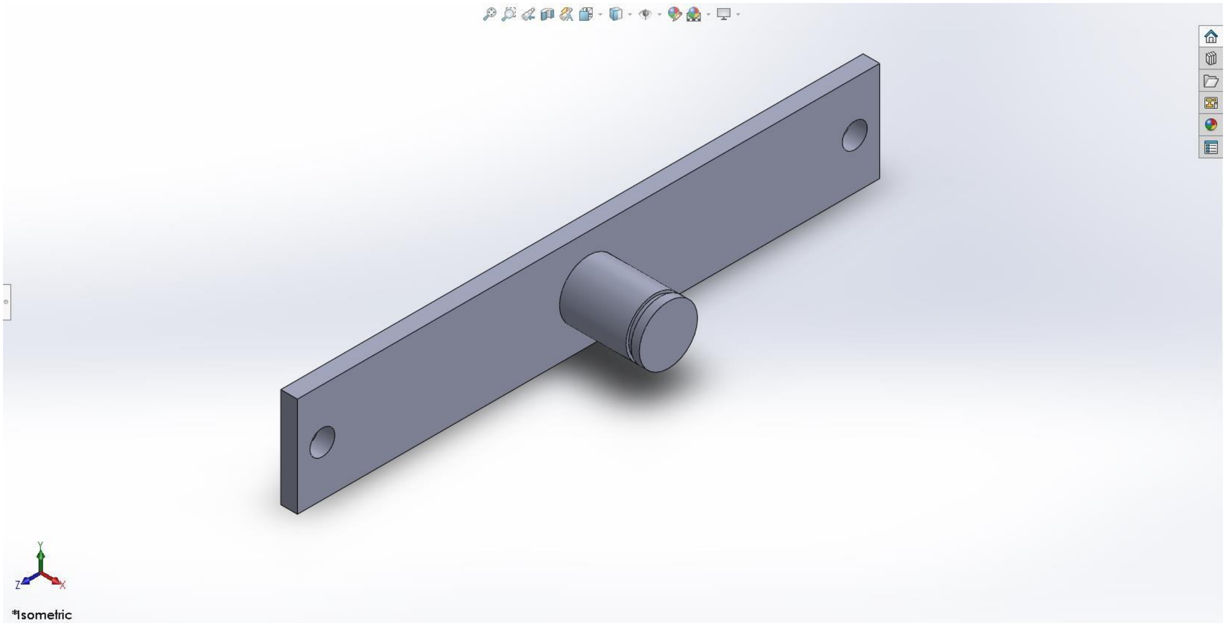

Figure 12: 3D View of the front closing strip for the OLED vacuum chamber. The dimensions for the front closing strip are 17.5 mm in length, 3 mm in width, and 0.5 mm in height. It also consists of a single groove of 2 mm depth.

The motivation behind the selected dimensions for the vacuum chamber was that the overall size of OLEDs is usually small. There is an opening in the front of the vacuum chamber to facilitate the sliding of OLED into and out of the chamber. The design contains an impression in the vacuum chamber to ensure that OLED fits that space. The overall dimensions of the surrounding walls are also kept narrow. The vacuum chamber design contains holes to ease the holding of wires and make electrical connections. The top surface of the vacuum chamber is kept transparent so that the OLED's working mechanism and light generation process can be observed and monitored. The design consists of handles on the front and back sides to hold the chamber easily.

4.3 CFD Simulation

The ANSYS CFD simulation methodology for the OLED vacuum chamber involves a systematic approach to model fluid flow and pressure distribution within the chamber accurately. The simulation process comprises the following steps:

4.3.1 Domain Creation

The different openings for the OLED vacuum chamber were adjusted by creating plane surfaces so that the vacuum chamber is fully closed on all sides, as seen in Figure 13.

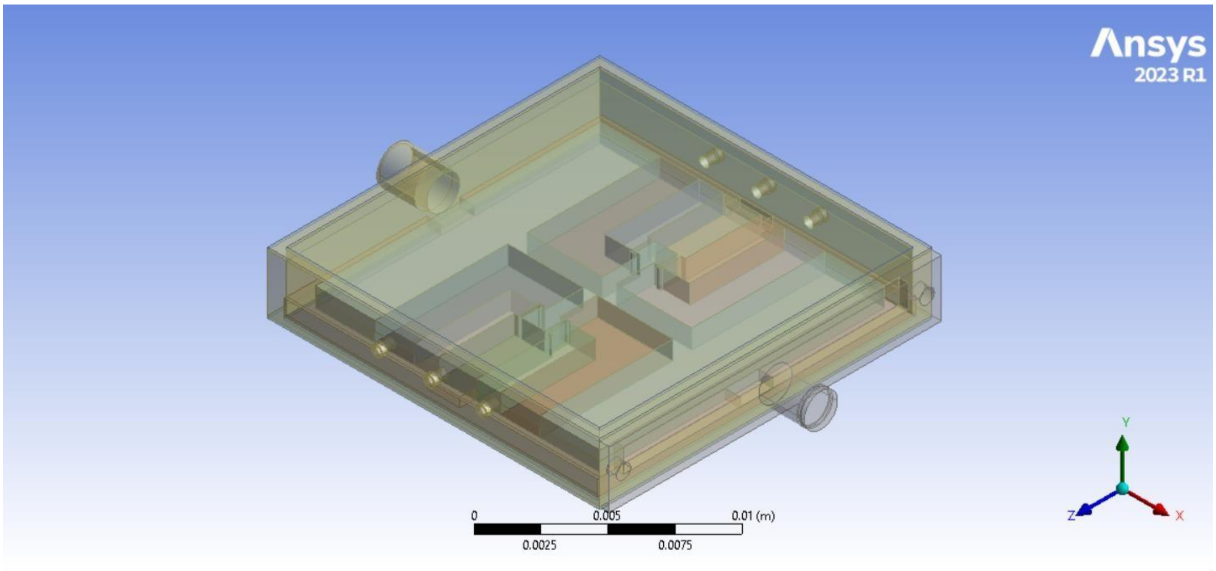

Figure 13: Geometrical domain of the OLED vacuum chamber. In the CFD simulation, plane surfaces were created to adjust the different openings of the OLED vacuum chamber to ensure it was fully closed on all sides.

Figure 13 shows the geometrical domain of the OLED vacuum chamber. All sides are fully closed, as seen in the figure.

4.3.2 Mesh Generation

Generating a high-quality mesh for the computational domain using appropriate meshing techniques enables capturing a proper level of details during the flow simulation. For this purpose, the structured mesh was defined for all the outside walls of the chamber. In contrast, the unstructured mesh of high mesh density was described for the inside chamber to fully capture the flow phenomenon inside the chamber, as seen in Figure 14.

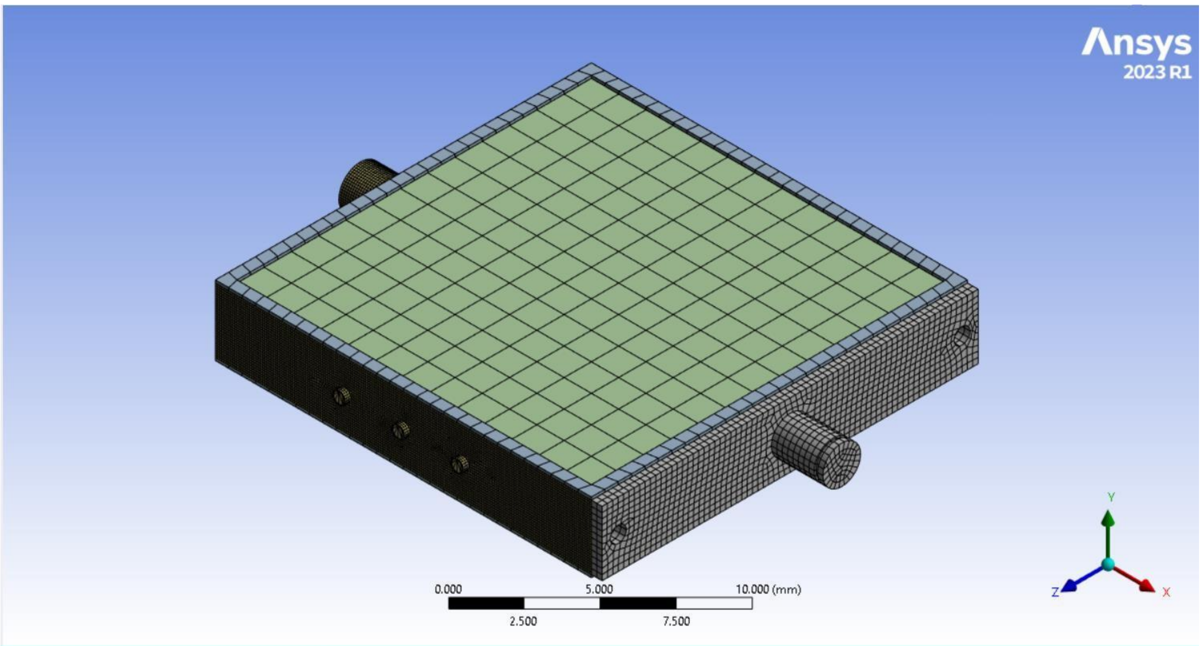

Figure 14: Mesh domain defined for the OLED vacuum chamber. Structured mesh was specified for all the outside walls of the chamber. An unstructured mesh with high mesh density was defined for the inside chamber to capture the flow entirely inside the chamber.

Figure 14 represents the mesh domain defined for the OLED vacuum chamber. For outside walls, structured mesh was defined. Inside the chamber, an unstructured mesh with high mesh density was defined.

4.3.3 Boundary Conditions

a) Pressure Outlet Boundary Condition: This boundary condition was applied to the vacuum chamber outlet. The initial pressure value of -25331.25 Pa was used for the initial simulation. A parametric sweep from -25331.25 Pa to -202650 Pa was also applied to understand the effect of increasing vacuum pressure inside the chamber.

b) Wall Boundary Condition: This was applied to the internal surfaces of the chamber, as seen in Figure 15.

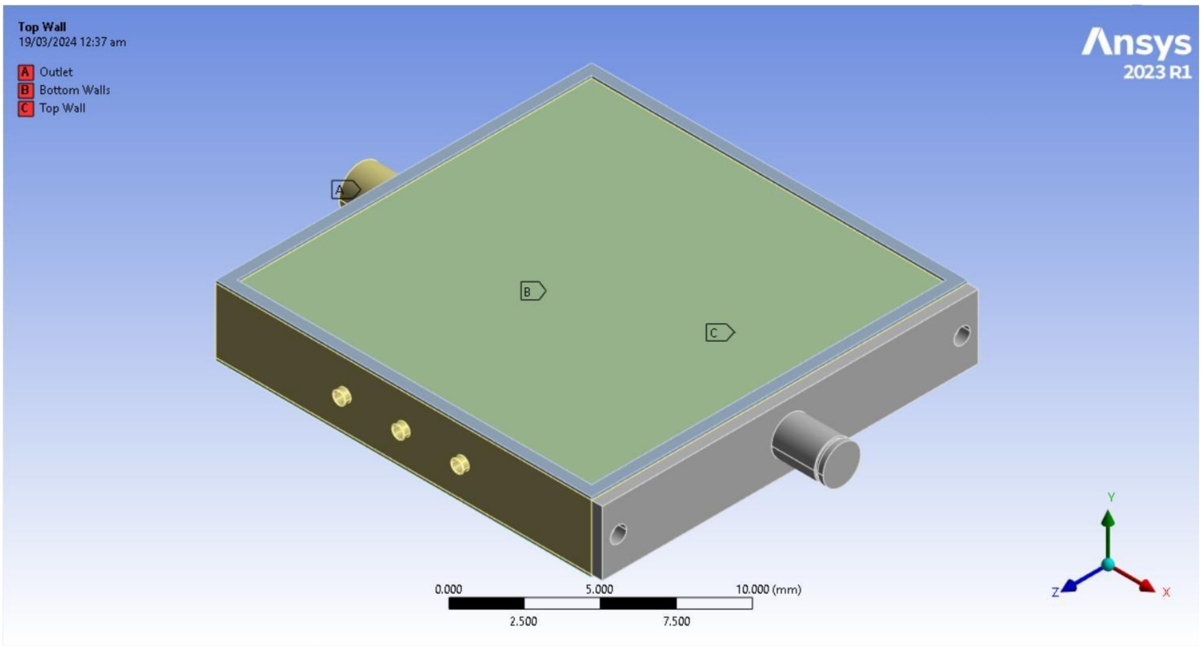

Figure 15: Boundary conditions applied to the OLED vacuum chamber. Pressure outlet boundary condition was applied to the vacuum chamber outlet. Wall boundary condition was applied to the internal surfaces of the chamber.

Figure 15 is the visual representation of the applied boundary conditions to the OLED vacuum chamber. A pressure outlet boundary condition was used for the vacuum chamber outlet, and a wall boundary condition was used for internal surfaces.

4.3.4 Fluid Properties

Appropriate fluid properties were defined for the air inside the OLED vacuum chamber. The values used for density and viscosity are 1.225 kg/m3 and 1.7894e-05 kg/m-s, respectively.

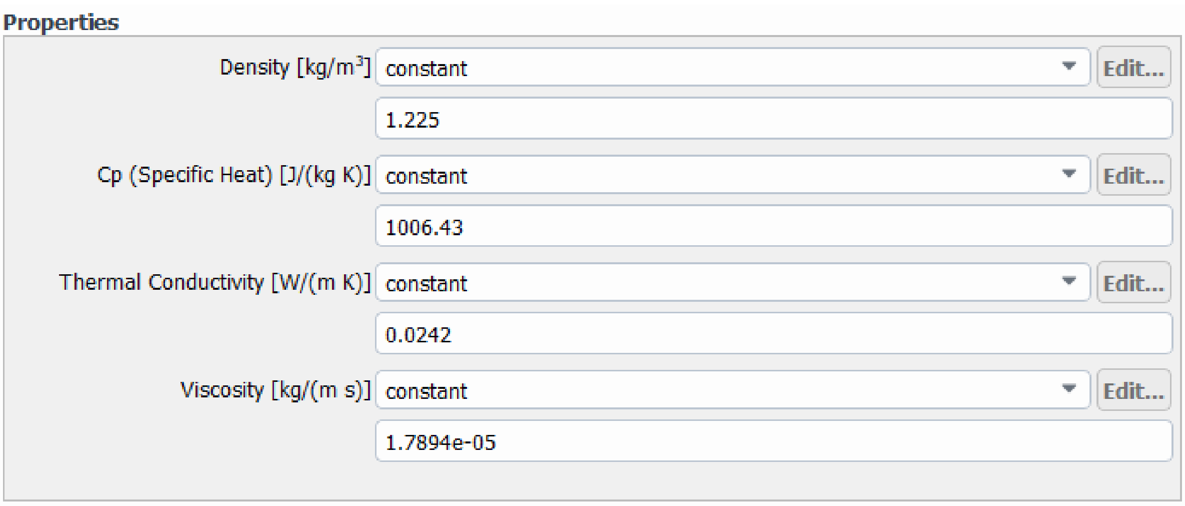

Figure 16: Fluid properties defined for the air inside the OLED vacuum chamber. Values of density, specific heat, thermal conductivity, and viscosity.

Figure 16 represents the selected values of different fluid properties of the air inside the OLED vacuum chamber. It shows the density values, specific heat, thermal conductivity, and viscosity.

4.3.5 Solver Selection and Setup

The pressure-based solver was selected to solve the governing equations of the fluid flow. The turbulence model employed for the simulation was the k-epsilon turbulence model. The k- epsilon turbulence model was selected due to its established reliability, computational efficiency, and versatility. The k-epsilon model offers robustness and stability across various flow regimes, ensuring reliable convergence of solutions. The low computational cost makes it well suited for performing parametric sweeps, facilitating comprehensive analysis and optimization of the chamber design within reliable computational resources.

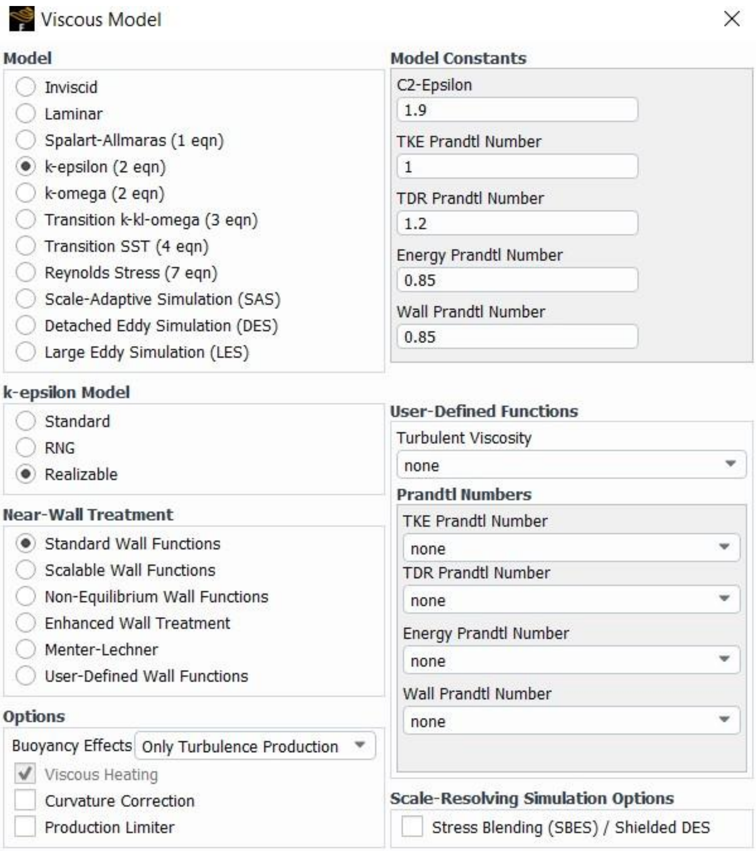

Figure 17: Specifications of selected turbulence model

Figure 17 shows the specifications of the selected turbulence model, i.e., the k-epsilon model.

5 Results and Discussion

Pressure distribution inside the vacuum chamber is the most critical parameter for the optimal performance of OLEDs. If the proper pressure is not maintained within the vacuum chamber, the performance of the OLED will be hindered or even lead to its failure. Therefore, the vacuum chamber is defined as sustaining pressure when suction is applied at the outlet to create a vacuum inside the chamber. For this purpose, different vacuum pressures were used at the outlet of the vacuum chamber to investigate the pressure distribution inside the OLED vacuum chamber, as seen in Figure 18.

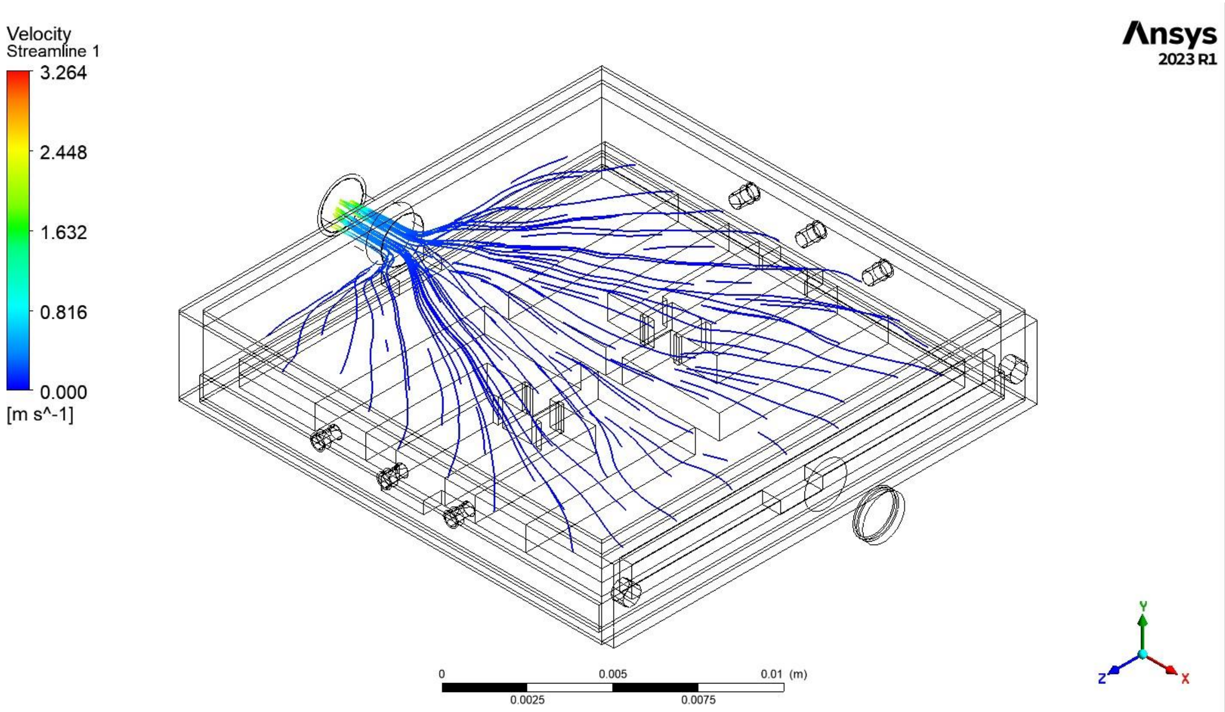

Figure 18: Air flow distribution inside the OLED vacuum chamber at -101325 Pa pressure. The flow is sucked uniformly throughout the chamber with the help of a vacuum pump at the top/left opening. The airflow velocity is high closer to the outlet in the range of 1.632 ms^{-1} to 2.448 ms^{-1}. The air is uniformly distributed across the vacuum chamber in all directions. The uniform distribution indicates that all the components are in place and the design has no irregularity.

The overall process behind the OLED vacuum chamber design is to apply suction pressure at the chamber outlet. As the suction pressure is applied, air flows uniformly from all sides of the vacuum chamber from the inside to the outlet. The suction pressure is gradually increased to understand the vacuum-creation process inside the chamber. As the suction pressure outside is increased, the pressure inside the chamber decreases, and the air flows from inside to the outlet in a uniform manner. The uniform air flow indicates a successful vacuum chamber design creation, as there are no irregularities in the design, and it is properly sealed.

The suction pressure varied from -25331.25 Pa to -202650 Pa. The pressure inside the chamber decreased and followed the same pattern for every suction pressure test value.

Initially, the pressure was set equal to -25331.25 Pa at the outlet of the OLED vacuum chamber while applying no-slip boundary conditions at the walls inside the vacuum chamber. This setup established a baseline understanding of pressure distribution under typical operating conditions. Subsequently, the effect of an increase in vacuum pressure was also investigated to understand the pressure distribution inside the vacuum chamber. For this purpose, the pressure was varied from -25331.25 Pa to -202650 Pa, and a simulation was performed to observe the pressure inside the OLED vacuum chamber, as seen in Figure 24. It becomes clear from the simulation results that as the outlet pressure for suction increases, the inside pressure decreases following the same pattern. The minimum inside pressure is observed at -25331.25 Pa. It corresponds to -0.00256 Pa inside the vacuum chamber, while the pressure decreases to -0.069125 Pa at -202650 Pa.

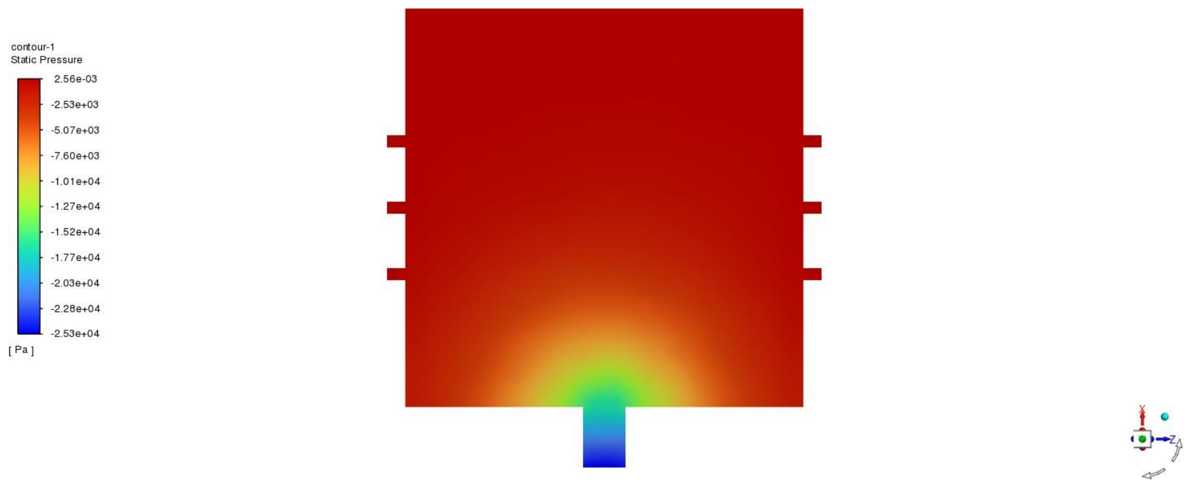

Figure 19: Pressure distribution along xy-plane inside the OLED vacuum chamber at -25331.25 Pa pressure. The lowest pressure, i.e., -2.53e4, is experienced at the bottom opening, where the vacuum pump is applied while the flow is sucked uniformly from the OLED vacuum chamber. The contour plot clearly shows that the pressure is higher inside the vacuum chamber, and when a suction pressure is applied at the outlet, the lowest pressure value is at the opening. The color strip on the left side indicates the value of static pressure. Red indicates the highest pressure, and blue indicates the lowest pressure. The flow is from higher pressure to lower pressure. There is a uniform flow from the inside of the vacuum chamber to the outside. This indicates that a vacuum is successfully created inside the chamber as suction pressure is applied to the opening.

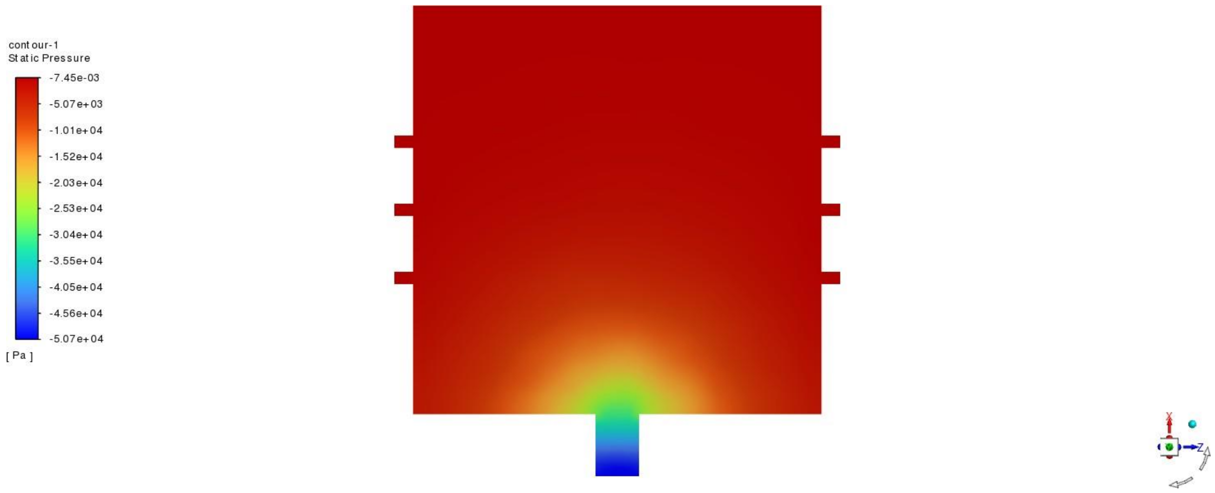

Figure 20: Pressure distribution along xy-plane inside the OLED vacuum chamber at -50662.50 Pa pressure. The lowest pressure, i.e., -5.07e4, is experienced at the bottom opening, where the vacuum pump is applied while the flow is sucked uniformly from the OLED vacuum chamber. The suction pressure value is increased to see the behavior inside the vacuum chamber. The contour plot shows the same behavior. The pressure is lowest at the point where the suction pump is applied and highest inside the chamber. A flow from inside to outside indicates a successful vacuum creation inside the chamber since the flow is uniform from inside the chamber to the outside. There are no leakages in the chamber design, and the components are correctly sealed.

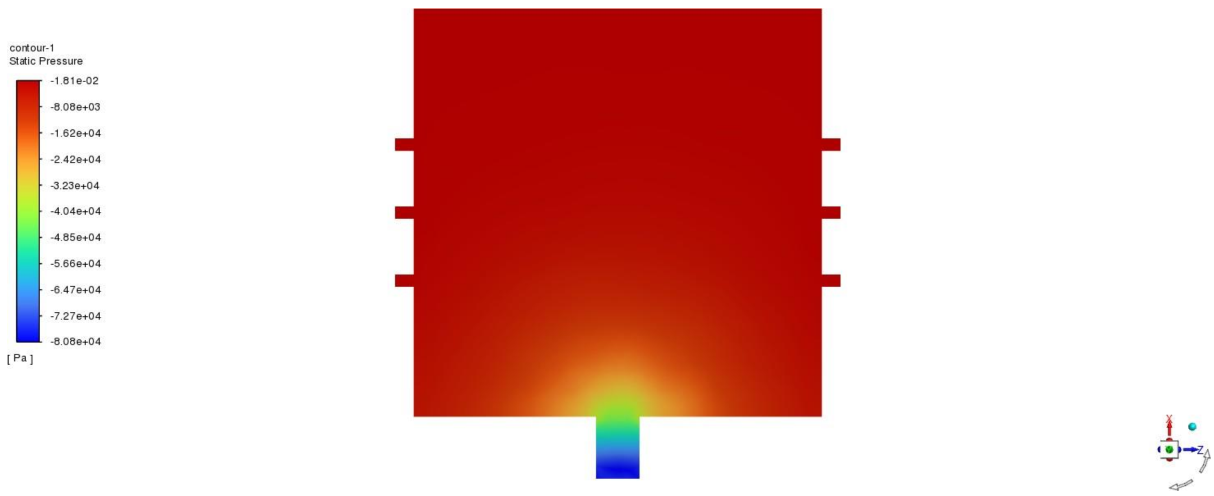

Figure 21: Pressure distribution along xy-plane inside the OLED vacuum chamber at -75993.75 Pa pressure. The lowest pressure, i.e., -8.08e4, is experienced at the bottom opening, where the vacuum pump is applied while the flow is sucked uniformly from the OLED vacuum chamber. The suction pressure is further increased, and the trend is the same. A uniform flow from the inside of the vacuum chamber to the outlet, as shown in the contour plot. Red indicates high pressure inside the chamber, and blue indicates lower pressure at the suction outlet. The uniformity in the flow inside the chamber indicates vacuum creation inside the chamber. If there were any irregularities in the design, the contour plot would have shown different colors at different points in the chamber.

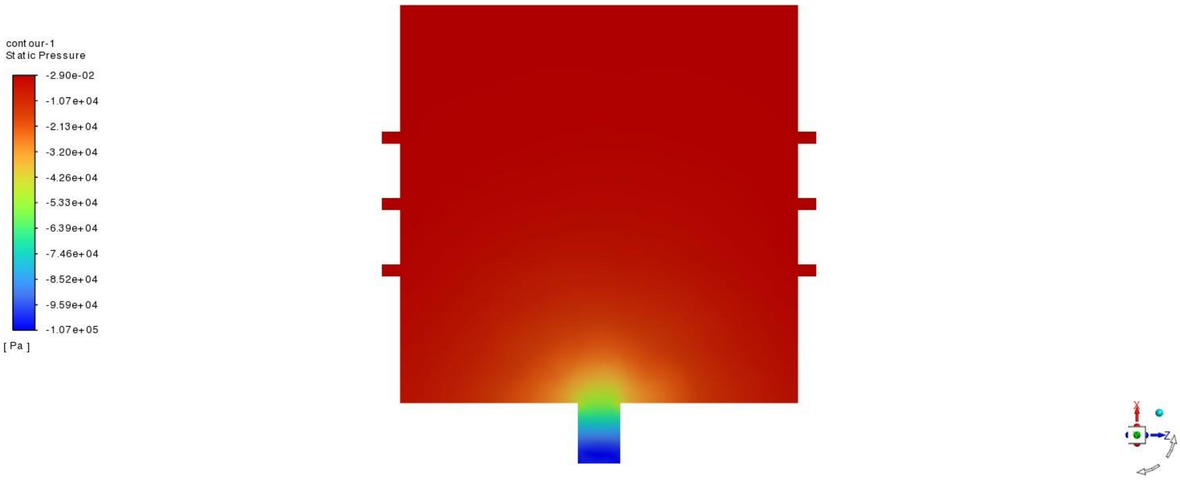

Figure 22: Pressure distribution along xy-plane inside the OLED vacuum chamber at -101325 Pa pressure. The lowest pressure, i.e., -1.07e4, is experienced at the bottom opening, where the vacuum pump is applied while the flow is sucked uniformly from the OLED vacuum chamber. The suction pressure is increased further to ensure no irregular behavior, and a vacuum is successfully created inside the chamber. The gradual increase in the suction pressure tests the behavior of vacuum creation inside the chamber. As we increase the suction pressure, the trend of vacuum creation is the same inside the chamber. The uniformity of flow inside the chamber indicates the successful design creation. This contour plot shows the lowest pressure value at the vacuum chamber's opening in blue.

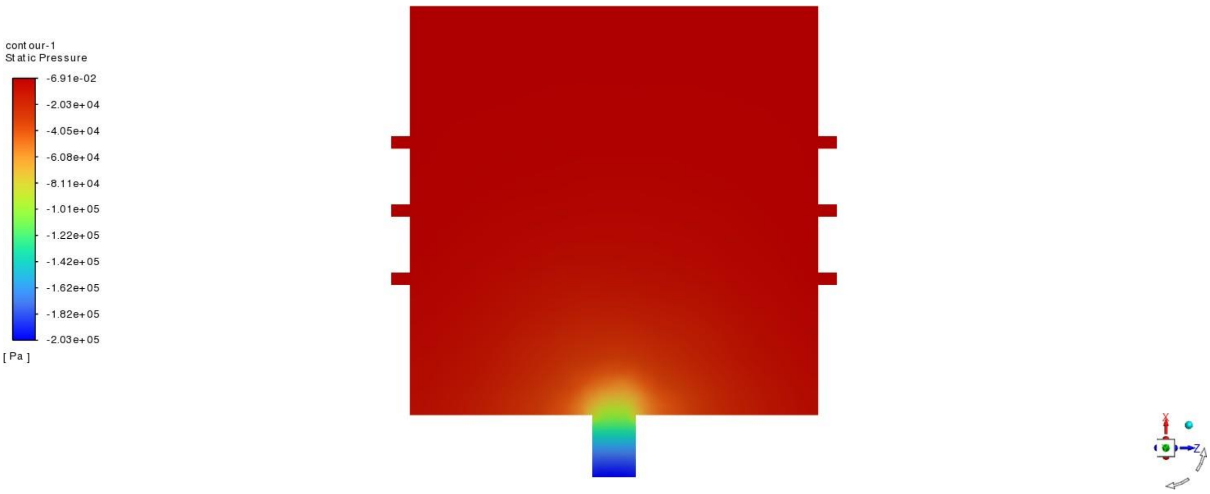

Figure 23: Pressure distribution along xy-plane inside the OLED vacuum chamber at -202650 Pa pressure. The lowest pressure, i.e., -2.03e4, is experienced at the bottom opening, where the vacuum pump is applied while the flow is sucked uniformly from the OLED vacuum chamber. This contour plot also clearly shows that there is uniform flow within the vacuum chamber, the pressure is uniformly distributed, and as a suction pressure is applied, the air flows uniformly from inside to outside, creating a vacuum. The suction pressure is increased to the highest test value in this case. At the opening of the OLED chamber, the pressure is lowest, and the pressure is highest inside the vacuum chamber. As the suction is applied, air uniformly flows from all parts of the vacuum chamber to the outlet. As a result, a vacuum is created inside the chamber.

A parametric sweep is performed to vary a parameter systematically through a range of values. These parameters vary according to the requirement. The purpose of changing the values of the parameter is to study its effect on the outcome of the model. The primary components of a parametric sweep include defined parameters, range, simulations, and analysis. In a parametric sweep, the first step is to define the model and select the parameters. After that, the simulation software is configured to run the iterations and execute the simulations. The data obtained from the simulations is collected and analyzed using graphs to interpret. The parametric sweep applications include design optimization, sensitivity analysis, and overall evaluation of the performance of a model. The complex engineering models can be optimized using a parametric sweep by varying the parameters and evaluating the results.

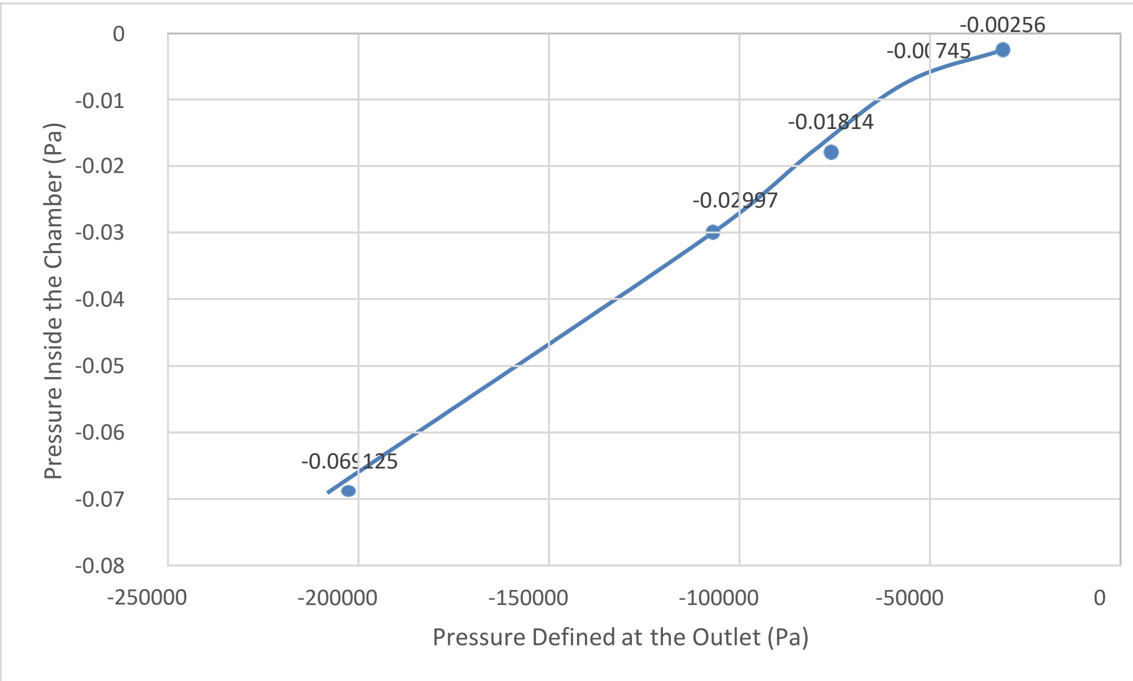

Figure 24: Parametric sweep for pressure inside the OLED vacuum chamber. The X-axis indicates the pressure defined at the outlet of the chamber. The Y-axis indicates the pressure inside the chamber. As the suction pressure increases, the pressure inside the vacuum chamber decreases, indicating a vacuum's creation.

In our case, the parametric sweep is done for the pressure inside the OLED vacuum chamber using ANSYS software. The pressure varied from -25331.25 Pa to -202650 Pa to observe the pressure inside the OLED vacuum chamber, as seen in Figure 24. It is clear from the graph that as the outlet pressure for suction increases, the inside pressure decreases. The minimum inside pressure is observed at -25331.25 Pa, corresponding to -0.00256 Pa inside the vacuum chamber, while the pressure decreases to - 0.069125 Pa at -202650 Pa.

6 Conclusion

This work extensively explores Organic light-emitting diodes (OLEDs),encompassing their fundamental principles, device structure, operational mechanisms, common challenges, and encapsulation strategies. A deeper understanding of their unique capabilities and potential applications across the industry is attained by delving into the intricate physics underpinning OLED operation, including electroluminescence and charge carrier dynamics.

The investigation into OLED degradation elucidates the factors contributing to device performance decline over time, highlighting the importance of robust encapsulation techniques and meticulous design considerations to mitigate these effects. The critical role of precise pressure control in ensuring optimal design fabrication and performance is underscored through comprehensive analysis and simulation of the OLED vacuum chamber. Integrating computational fluid dynamics (CFD) simulation and detailed design methodology offers valuable insights into pressure distribution dynamics within the chamber, guiding the development of more efficient manufacturing processes.

Moreover, the investigation of System Operation Aeres as a tool for automating deposition processes within the OLED vacuum chamber demonstrates the potential for enhanced efficiency and reliability in OLED manufacturing. By streamlining process execution and providing real-time control over deposition parameters, Aeres facilitates greater flexibility and responsiveness in adapting to changing requirements and experimental conditions. Integrating Aeres with the deposition system represents a significant advancement in process automation and quality control, laying the groundwork for future innovations in OLED manufacturing.

Looking ahead, several avenues for further research and development in the field of OLED technology present themselves. Continued optimization of encapsulation techniques, such as thin-film barriers and hybrid organic-inorganic materials, holds promise for improving OLED devices' long-term stability and reliability. Additionally, advancements in material sciences and fabrication processes offer opportunities to enhance device performance, efficiency, and versatility. Research into novel materials with tailored optoelectronic properties and innovative manufacturing approaches could pave the way for developing next-generation OLEDs with enhanced functionality and durability.

Furthermore, exploring emerging applications for OLED technology, including flexible and transparent displays, solid-state lighting, and wearable electronics, opens new avenues for innovation and commercialization. As OLEDs continue to evolve and mature, their integration into various consumer electronics, automotive displays, and architectural lighting systems is poised to transform how light is experienced and interacted with.

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Appendices

2. Mesh Report

Table 2. Mesh Information for FLU

Domain	Nodes	Elements
oled	1108	433
oled_2	1206	550
oled_closing_strip	4403	4104
oled_enclosure	119645	99159
oled_enclosure_bottom	3390	2206
oled_enclosure_top	824	277
solid	6041	25555
All Domains	136617	132284

4. User Data

Figure 1. Velocity Streamlines

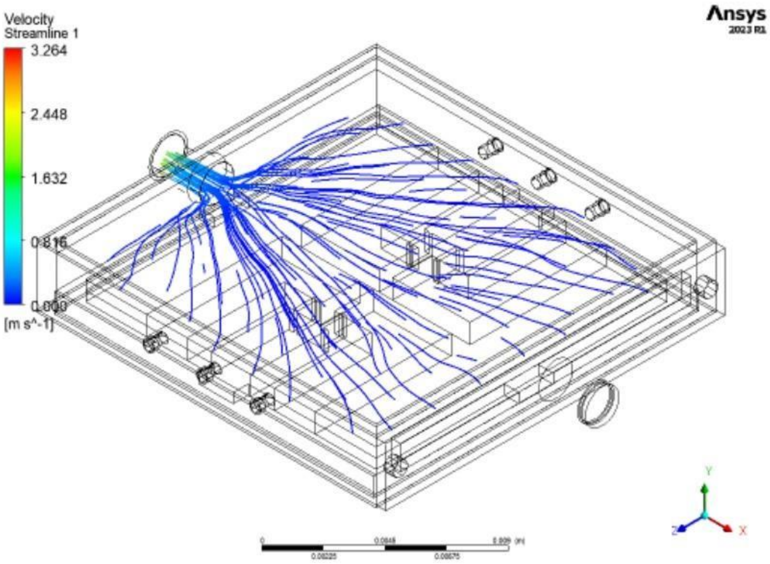

Figure 2. Pressure Contours

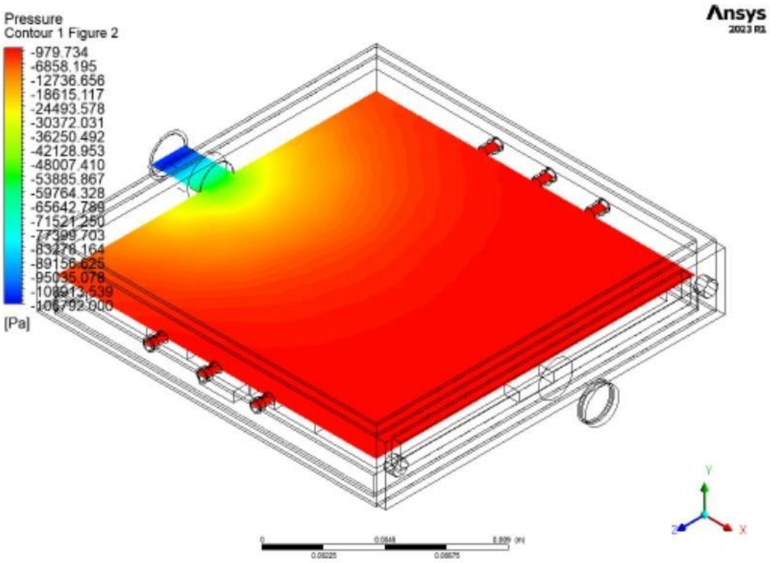

Figure 3. Velocity and Pressure Distribution