I'm not a robot

One or more of the following disciplines may be involved in solving a particular thermal engineering problem:ThermodynamicsA knowledge of thermodynamics is essential to nuclear engineers, who deal with nuclear power reactors. Thermodynamics is the science that deals with energy production, storage, transfer and conversion. It studies the effects of work, heat and energy on a system. Thermodynamics is both a branch of physics and an engineering science. The physicist is normally interested in gaining a fundamental understanding of the physical and chemical behavior of fixed quantities of matter at rest and uses the laws of thermodynamics to relate the properties of matter. Engineers are generally interested in studying energy systemsand how they interact with their surroundings. Our goal here will be to introduce thermodynamics as the energy conversion science, to introduce some of the fundamental concepts and definitions that are used in the study of engineering thermodynamics. These fundamental concepts and definitions will be further applied to energy systems and finally to thermal or nuclear power plants.Fluid MechanicsCFD numerical simulation Source: CFD development group – hzdr.deFluid mechanics is the branch of thermal engineering concerned with the mechanics of fluids (liquids, gases, and plasmas) and the forces on them. It can be divided into fluid statics, the study of fluids at rest; and fluid dynamics. Fluid dynamics is a subdiscipline of fluid mechanics that deals with fluid flow. Fluid dynamics is one of the most important of all areas of physics. Life as we know it would not exist without fluids, and without the behavior that fluids exhibit. The air we breathe and the water we drink (and which makes up most of our body mass) are fluids. Fluid dynamics has a wide range of applications, including calculating forces and moments on aircraft (aerodynamics), determining the mass flow rate of water through pipelines (hydrodynamics).Fluid dynamics is an important part of most industrial processes; especially those involving thetransfer of heat. In nuclear reactors the heat removal from the reactor core is accomplished by passing a liquid or gaseous coolant through the core and through other regions where heat is generated. The nature and operation of the coolant system is one of the most important considerations in the design of a nuclear reactor.Heat Transfer and Mass TransferHeat transfer is an engineering discipline that concerns the generation, use, conversion, and exchange of heat (thermal energy) between physical systems. In power engineering it determines key parameters and materials of heat exchangers. Heat transfer is usually classified into various mechanisms, such as:Heat Conduction. Heat conduction, also called diffusion, occurs within a body or between two bodies in contact. It is the direct microscopic exchange of kinetic energy of particles through the boundary between two systems. When an object is at a different temperature from another body or its surroundingsHeat Convection. Heat convection depends on motion of mass from one region of space to another. Heat convection occurs when bulk flow of a fluid (gas or liquid) carries heat along with the flow of matter in the fluid.Thermal Radiation. Radiation is heat transfer by electromagnetic radiation, such as sunshine, with no need for matter to be present in the space between bodies.In engineering, the term convective heat transfer is used to describe the combined effects of conduction and fluid flow. At this point, we have to add a new mechanism, which is known as advection (the transport of a substance by bulk motion). From the thermodynamic point of view, heat flows into a fluid by diffusion to increase its energy, the fluid then transfers (advects) this increased internal energy (not heat) from one location to another, and this is then followed by a second thermal interaction which transfers heat to a second body or system, again by diffusion. Steam quality and steam purity are topics that often get confused with each other. Distinguishing the difference between the two will help you understand the unique impacts they have on a steam system. Steam quality is a measure of moisture in the steam expressed as the percentage of steam vapor in the steam/water mixture. For example, 99% steam quality contains 1% liquid water. Once steam quality is known, the percent moisture can be calculated using Equation 1. Equation 1: % Moisture = 100 – % Quality Understanding steam quality requires understanding vapor-liquid equilibrium in water. As Figure 1 illustrates, when heat is added to subcooled liquid water, it proceeds to the saturated liquid curve and becomes a saturated liquid (moving from incoming city water to point A). At the saturation point (Point A in the figure below), any heat added to the water will form a vapor and the temperature will remain the same because all additional enthalpy (heat energy) being added to the system is being used to change the phase of the water from liquid to vapor. A saturated fluid in the liquid-vapor region at a given pressure always has the same temperature. This explains why the temperature in the waterside of a boiler or a deaerator can be predicted at a given pressure. As heat continues to be added to the water, more steam forms, but the solution remains in equilibrium (moving from points A → B in the figure below) and the temperature of the fluid remains the same. The region between points A and B is where most steam exists in traditional boiler applications with the preference being closer to B. At point B, the water reaches the vapor saturation point for that pressure. Adding heat to water above the saturation point superheats the steam. Figure 1: Water Pressure vs. Enthalpy Curve Steam quality is the percentage of steam present in a mixture of steam and moisture (between points A and B). When boilers produce steam, unless it's superheated, it begins to lose quality (condense back to liquid by losing heat) as soon as it leaves the boiler. Wet steam is less efficient and potentially damaging to system equipment. Poor steam quality is typically the result of one of the following: Malfunctioning steam traps Lack of insulation on steam lines Boiler water carryover In an autoclave or sterilizer application, manufacturers typically require steam quality within a band to ensure the steam isn't too hot or too wet. Steam that is too wet doesn't have sufficient energy to sterilize equipment, and steam that is superheated may be too hot. Steam quality is extremely important in applications where steam is turning a turbine because water condensing on the blades could result in turbine blade erosion and the turbine losing balance. Measuring steam quality requires a calorimeter (Separating Calorimeter or Throttling Calorimeter) and accurate readings of steam temperature, pressure, and steaming rate. It can be difficult to measure. Steam purity is a measure of the amount of solids (entrained or dissolved) present in the steam and is reported as ppm or ppb. Poor steam purity is typically the result of one of the following: Boiler water carryover Accelerated corrosion rates in steam lines Process contamination Steam purity is much more of a concern in Industrial boilers without superheaters (Max 1 ppm TDS), Superheated Industrial Boilers (Max 20 ppb Sodium & Max 20 ppb Silica), and Healthcare sterilizer applications. Steam Purity can also be much easier to measure. One should consult equipment manufacturer manuals and guidelines for steam purity and quality requirements. A customized approach may be required to solve steam purity and/or quality issues. Chem-Aqua is a global leader in custom-designed programs for boiler, cooling, and process water systems. Written by: Tyler Anderson What is steam quality? Why is steam quality important? What are the effects of steam quality? How is steam quality measured? What Is Steam Quality? Steam quality is the proportion of saturated steam (vapor) in a saturated condensate (liquid)/steam (vapor) mixture. A steam quality of 0 indicates 100% liquid (condensate), while a steam quality of 100 indicates 100% steam. One (1) lb of steam with 95% steam and 5% percent of liquid entrainment has a steam quality of 0.95. The measurements needed to obtain a steam quality measurement are temperature, pressure, and entrained liquid content. A high percentage (88% or more) of industrial steam systems use saturated steam for process applications. Saturated steam (meaning steam that is saturated with energy) is completely gaseous and contains no liquid. The boiler operation uses chemical energy from a fuel source to deliver energy to the boiler water. Inside the boiler, liquid gains energy from the combustion process and changes state into saturated steam. Water enters the boiler at point A and the water gains sensible energy (hf) to point B. The change of state is referenced as point B on the chart. As the saturated steam acquires more energy from the boiler combustion process, the steam achieves a high quality, as represented on the chart by moving left to right, from points B to C. The increase in energy gained by the steam from points C to D goes toward the superheat of the vapor. There exists a directly proportional relationship between temperature and pressure in saturated steam. That is, as the temperature increases, so does the pressure. Illustrated by the "lines of constant pressure" on the graph, more sensible energy (hf) is needed for water to transition from point A to point B and become a vapor. When steam enters the process, the energy level goes from right to left as the process absorbs the energy from the steam. Why Steam Quality Is Important Today's manufacturing techniques of heat transfer, control, and standards are all dedicated to improving and providing the highest quality product to the market place. To attain the highest quality, each manufactured component of the final product is inspected repeatedly, and measured for its quality to ensure that it meets the manufacturer's and consumer's expectations. Steam is a vital and critical part in producing the final product; therefore, steam quality should be one of the main measurable points in producing a product in today's manufacturing facility. All heat transfer components (shell/tube, plate/frame, plate/coil, tracing, etc.) base performance calculations on 100% steam quality, unless the manufacturer is informed by the end user that the steam quality is lower than 100%. Unfortunately, steam quality is typically not monitored closely and is assumed to be 100% quality. Therefore, issues that arise from poor steam quality are blamed on some other item in the system. Based on field documentation by Swagelok Energy Advisors Inc., a high percentage of steam systems are operating below acceptable steam quality levels. What Are the Effects of Steam Quality? Low steam quality affects steam system operations in many ways. Reduced heat transfer efficiency: The major problem with low steam quality is the effect on the heat transfer equipment and process. In some cases, low steam quality can reduce heat transfer efficiency by more than 65%. The liquid entrained in the steam has sensible energy (16% estimated – varies with pressure) which has a significantly lower amount of energy than the steam vapor's latent energy (94%). Therefore, less usable energy is being delivered to the steam process equipment. Also, the additional liquid (low steam quality) collects on the wetted surface of the heat exchanger, causing an additional build up of a liquid, which reduces the ability of the steam's latent energy to be transfer to the product. Premature valve failure: Liquid passing through steam control valves will erode the internals of the valves, causing premature failure. Internal turbine component failures: Liquid introduced with the steam in a saturated turbine operation will reduce the life expectancy of the internal components. Waterhammer: Steam systems are usually not designed to accommodate the additional liquid in steam. Additional liquid creates the chance for waterhammer to occur. Waterhammer is a safety issue, and may cause premature failure in the steam system. How Is Steam Quality Measured? A true measurement of steam quality can be obtained from the use of a throttling calorimeter and Ganapathy's steam plant calculations. Unfortunately, most industrial plants do not have the luxury or capability of doing the testing. Another way to measure steam quality is relying on the basics of steam. Saturated steam is a dry invisible gas and only becomes visible with the entrained air or liquid. Therefore, opening a steam valve and allowing steam to be released into the atmosphere provides an estimate of the steam quality in the system. Examples: Picture number 1 indicates an acceptable steam quality. The discharge from the valve through the tube is almost invisible. Picture number 2 shows the discharge from the valve off the steam line to be very visible with liquid being discharged with the steam vapor. Steam quality is not acceptable for the process. Picture number 3 shows the discharge from the valve off the steam line to be very visible with liquid being discharged with the steam vapor. Steam quality is not acceptable for the process. Roadmap to Ensure a High Steam Quality The following items will ensure a high steam quality: Insulate steam lines and components Establish proper steam line drip leg steam trap stations Develop proper startup procedures Implement a proactive boiler chemical program Implement a proactive steam system management program Install steam separators (mechanical coalescing design), if needed For more information, visit www.swagelokenergy.com. The above material is part of Swagelok Energy Advisor's series of Best Practice papers, authored by Kelly Paffel. Kelly is a recognized authority in steam and condensate systems. He is a frequent lecturer and instructor on the technical aspects of steam systems. In addition, Kelly has published many papers on the topics of steam system design and operation. Over the past 30 years, he has conducted thousands of steam system audits and training sessions in the United States and overseas, which has made Kelly an expert in trouble-shooting actual and potential problems in the utilities of steam. Kelly is a member of the U.S. Department of Energy's (DOE) Steam Best Practices and Steam Training Committees. See also: Properties of SteamAs seen from the phase diagram of water, in the two-phase regions (e.g.,, on the border of vapor/liquid phases), specifying temperature alone will set the pressure, and specifying pressure will set the temperature. But these parameters will not define the volume and enthalpy because we will need to know the relative proportion of the two phases present.The mass fraction of the vapor in a two-phase liquid-vapor region is called the vapor quality (or dryness fraction), x, and it is given by the following formula:The value of the quality ranges from zero to unity. Although defined as a ratio, the quality is frequently given as a percentage. From this point of view, we distinguish between three basic types of steam. It must be added, at x=0, we are talking about the saturated liquid state (single-phase).Wet SteamDry SteamSuperheated SteamThis classification of steam has its limitation. Consider the system's behavior which is heated at a pressure that is higher than the critical pressure. In this case, there would be no change in phase from liquid to steam. In all states, there would be only one phase. Vaporization and condensation can occur only when the pressure is less than the critical pressure. The terms liquid and vapor tend to lose their significance.See also: Saturation.See also: Throttling of Steam Share — copy and redistribute the material in any medium or format for any purpose, even commercially. Adapt — remix, transform, and build upon the material for any purpose, even commercially. The licensor cannot revoke these freedoms as long as you follow the license terms. Attribution — You must give appropriate credit , provide a link to the license, and indicate if changes were made . You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use. ShareAlike — If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original. No additional restrictions — You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits. You do not have to comply with the license for elements of the material in the public domain or where your use is permitted by an applicable exception or limitation . No warranties are given. The license may not give you all of the permissions necessary for your intended use. For example, other rights such as publicity, privacy, or moral rights may limit how you use the material. Open, fast, peer-reviewed 3 STEP PROCESS 3 Months to Publication Always Open for Submissions 26 Book Series Covering Diverse Scientific Fields ISSN + ISBN Our authors span the globe, including emerging researchers at science's cutting edge and esteemed Nobel Laureates. Contribute to this shared scientific journey and join us shaping the future. View All Authors and Academic Editors IntechOpen Journals are a new publishing venue for academics in areas of rapid interdisciplinary growth at the cutting edge of technology, environmental sciences and human health. Open Access & Open Science Rapid Publication And Dissemination Renowned Editorial Boards Technology Focused Aligned With United Nations Sdgs We connect you with peers all over the world and help you advance your career through wide readership, dissemination, and higher citation counts. Join IntechOpen in its mission to publish the best scientific research and increase the visibility of your work. Built by scientists, for scientists. We provide a unique personal approach, day-to-day support, and all the tools you need to make your work accessible worldwide. Our robust peer review ensures your work is suitable for publication and valuable to the scientific community. 23 April 2025 Read more 25 March 2025 Read more 08 July 2024 Read more 07 June 2023 Read more 22 May 2024 Read more 11 March 2024 Read more 26 June 2023 Read more 28 March 2023 Read more 17 February 2023 Read more 15 September 2021 Read more Saturated steam, a critical phase of water, exhibits unique thermodynamic properties vital to numerous industrial processes. Specifically, the enthalpy of saturated steam, a measure of its total heat content, differentiates it from other phases of water, influencing its applications in systems like sterilization autoclaves. The American Society of Mechanical Engineers (ASME) provides stringent guidelines concerning the generation and handling of saturated steam to ensure safety and efficiency. Understanding what is saturated steam requires considering its state at the boiling point of water for a given pressure, defining its role in heat transfer mechanisms within thermal power plants. Saturated steam is a vital medium in numerous engineering applications, serving as a highly efficient and readily controllable energy source. Its unique properties, stemming from its state of thermodynamic equilibrium, make it indispensable across diverse industries. This section will introduce the fundamental characteristics of saturated steam and its significance in modern engineering. Defining Saturated Steam: Equilibrium at the Boiling Point Saturated steam is defined as steam that exists in equilibrium with boiling water at a given pressure. This means that the rate of water molecules transitioning into the gaseous phase (steam) is equal to the rate of steam molecules condensing back into liquid water. This dynamic equilibrium is crucial to understanding the behavior and properties of saturated steam. It's not merely steam; it's steam at its boiling point for a specific pressure. Thermodynamic Equilibrium: Constant Temperature and Pressure A key aspect of saturated steam is its thermodynamic state. During the phase transition from water to saturated steam, the temperature and pressure remain constant. This is because the energy being added is used to overcome the intermolecular forces holding the water molecules together, rather than increasing their kinetic energy (which would raise the temperature). This constant temperature and pressure during phase change provide predictable and controllable energy transfer, a major advantage in many applications. This allows for precise control of processes utilizing this steam. Widespread Applications: Power, Heating, and Industry Saturated steam plays a pivotal role in a wide range of applications, including: Power generation: Driving turbines in power plants to produce electricity. Heating systems: Providing efficient and uniform heat distribution in industrial and commercial settings. Industrial processes: Serving as a heat source for various manufacturing processes, sterilization, and other applications. Its versatility and controllability make it a preferred choice over other energy transfer methods in many scenarios. Efficient Energy Transfer: Latent Heat of Vaporization The efficiency of saturated steam as an energy transfer medium is primarily due to its high latent heat of vaporization. This is the amount of energy required to convert water into steam at a constant temperature and pressure. When saturated steam condenses back into water, it releases this stored energy, providing a large amount of heat output at a constant temperature. This makes it a highly efficient and effective method for delivering thermal energy to various processes. The rapid and consistent heat transfer is particularly valuable. Fundamental Principles: Thermodynamics and Phase Transitions Saturated steam's utility stems from the fundamental laws of thermodynamics that govern its behavior. Understanding these principles, particularly concerning phase transitions, is crucial for effectively harnessing its power in diverse engineering applications. Thermodynamics in Steam Systems: The First and Second Laws The first and second laws of thermodynamics provide the theoretical framework for analyzing steam systems. First Law: Conservation of Energy The first law, the law of conservation of energy, dictates that energy within a closed system remains constant. In steam systems, this means that the total energy input, accounting for heat, work, and changes in internal energy, must equal the total energy output. This principle is fundamental for calculating the energy balance in boilers, turbines, and heat exchangers. It allows engineers to optimize system design for maximum energy efficiency, reducing losses and improving overall performance. For example, careful insulation of steam pipes minimizes heat loss to the surroundings, preserving the energy content of the steam for its intended purpose. Second Law: Entropy and Steam Processes The second law of thermodynamics introduces the concept of entropy, a measure of disorder or randomness within a system. It states that the total entropy of an isolated system can only increase over time or remain constant in ideal cases (reversible processes). In steam systems, entropy generation occurs due to factors like friction, heat transfer across a finite temperature difference, and throttling. Minimizing these irreversible processes is essential for maximizing the efficiency of steam-based power cycles. For example, the design of turbine blades aims to minimize frictional losses and ensure smooth steam flow, reducing entropy generation and improving turbine efficiency. Phase Transitions and Steam Formation The formation of saturated steam involves a phase transition from liquid water to the gaseous state. This transition is governed by specific thermodynamic conditions and processes. The Boiling Process and Influencing Factors Boiling occurs when the vapor pressure of the liquid equals the surrounding pressure. At this point, water molecules gain sufficient energy to overcome intermolecular forces and escape into the gaseous phase. Several factors influence the boiling process, including pressure, temperature, and the presence of impurities. Higher pressures require higher temperatures to initiate boiling, a crucial relationship that defines saturated steam's properties. The presence of dissolved gases can also affect boiling by altering the vapor pressure of the liquid mixture. These dissolved gases could come from system degradation or water treatment failures. Saturation Temperature and Saturation Pressure Saturation temperature is the temperature at which boiling occurs for a given pressure, while saturation pressure is the pressure at which boiling occurs for a given temperature. These two parameters are inextricably linked and define the state of saturated steam. Knowing either the saturation temperature or saturation pressure allows for the determination of all other thermodynamic properties of saturated steam using steam tables. For instance, at atmospheric pressure (approximately 101.3 kPa), the saturation temperature of water is 100°C. This means that water will boil and form saturated steam at 100°C when exposed to atmospheric pressure. Heat Transfer Mechanisms in Steam Systems Efficient heat transfer is paramount in steam systems, particularly in boilers and heat exchangers. The three primary modes of heat transfer – conduction, convection, and radiation – play distinct roles. Conduction, Convection, and Radiation Conduction involves heat transfer through a solid material due to a temperature gradient. In boilers, heat is conducted through the metal walls of the furnace to the water inside. Convection involves heat transfer through the movement of fluids (liquids or gases). In boilers, natural or forced convection circulates water, facilitating heat transfer from the heated walls to the bulk liquid. Radiation involves heat transfer through electromagnetic waves. In boilers, radiation from the combustion flame is a significant contributor to heating the water. Efficient Heat Transfer for Steam Generation Efficient heat transfer is critical for maximizing steam generation and minimizing fuel consumption. Boiler designs incorporate various features to enhance heat transfer, such as extended surfaces (fins) and optimized flow patterns. Scale buildup on heat transfer surfaces impedes heat transfer and reduces boiler efficiency; proper water treatment is required to prevent this. Properties of Saturated Steam Several key properties define saturated steam, dictating its behavior and suitability for specific applications. Latent Heat of Vaporization: The Stored Energy Latent heat of vaporization is the amount of energy required to convert a unit mass of liquid water into saturated steam at a constant temperature and pressure. This property is the reason why saturated steam can transfer large amounts of energy at a constant temperature. When steam condenses, it releases this latent heat, making it an efficient heat source. The high latent heat of vaporization of water makes saturated steam particularly effective for applications like heating and sterilization. The Pressure-Temperature Relationship The pressure and temperature of saturated steam are directly related. This relationship is defined by the saturation curve, which illustrates the boiling point of water at different pressures. As pressure increases, the saturation temperature also increases. This relationship is critical for controlling steam temperature and pressure in various applications. Boiling Point and Pressure The boiling point of water is dependent on the surrounding pressure. At higher pressures, the boiling point increases, and at lower pressures, it decreases. This principle explains why water boils at different temperatures at different altitudes. Understanding this pressure-temperature dependency is essential for designing steam systems operating at varying pressures and for ensuring consistent steam quality and performance. Key Properties and Calculations: Steam Tables and Quality To effectively utilize saturated steam, understanding how to determine its key properties is essential. Steam tables, also known as thermodynamic tables, are indispensable tools for engineers and technicians. These tables provide a comprehensive compilation of saturated steam properties at various pressures and temperatures. Furthermore, the concept of steam quality, often represented as the dryness fraction, significantly impacts steam performance and must be carefully considered. Understanding and Using Steam Tables Steam tables provide a wealth of information about the thermodynamic properties of water and steam at saturation conditions. They present data in a structured format, typically listing properties corresponding to specific pressure or temperature values. Data Included in Steam Tables The data included in steam tables typically includes: Pressure (P): Expressed in units like kPa, MPa, psi, or bar, pressure is a fundamental parameter defining the state of the steam. Temperature (T): The saturation temperature corresponding to the given pressure, usually in °C or °F. Specific Volume (v): The volume occupied by a unit mass of the substance. Steam tables usually list specific volume for both saturated liquid (vf) and saturated vapor (vg) phases. This property is crucial for determining the size of equipment and piping. Enthalpy (h): Representing the total heat content of the substance, enthalpy is provided for saturated liquid (hf), saturated vapor (hg), and the enthalpy of vaporization (hfg), also known as latent heat. Enthalpy values are essential for energy balance calculations. Entropy (s): A measure of disorder in the system. Similar to enthalpy, entropy values are provided for saturated liquid (sf) and saturated vapor (sg) to enable thermodynamic analysis of steam processes. Practical Examples of Property Determination Let's consider an example: suppose we want to find the properties of saturated steam at a pressure of 1.0 MPa. By consulting the steam tables, we can directly read the following values: Saturation Temperature (Tsat): Approximately 179.9 °C Specific Volume of Saturated Liquid (vf): Approximately 0.001127 m^3/kg Specific Volume of Saturated Vapor (vg): Approximately 0.1944 m^3/kg Enthalpy of Saturated Liquid (hf): Approximately 762.6 kJ/kg Enthalpy of Saturated Vapor (hg): Approximately 2778.1 kJ/kg Entropy of Saturated Liquid (sf): Approximately 2.139 kJ/kg·K Entropy of Saturated Vapor (sg): Approximately 6.586 kJ/kg·K These values are critical for designing and optimizing steam-based systems. For example, the large difference between hg and hf (the latent heat of vaporization) underscores steam's efficiency as an energy carrier. Understanding Steam Quality (Dryness Fraction) Steam flowing in a system is rarely entirely in the vapor phase. It often contains a mixture of saturated liquid water and saturated vapor. Steam quality, or dryness fraction (x), quantifies the proportion of vapor in the mixture. Definition and Implications Steam quality (x) is defined as the ratio of the mass of dry steam (vapor) to the total mass of the mixture (liquid + vapor): x = mass of dry steam / (mass of dry steam + mass of liquid water) A steam quality of 1.0 (or 100%) indicates dry saturated steam, while a quality of 0 indicates saturated liquid. A value between 0 and 1 represents wet steam, a mixture of liquid and vapor. Steam quality has significant implications for steam performance. Lower steam quality (higher moisture content) can lead to: Reduced heat transfer efficiency due to the presence of liquid water on heat exchange surfaces. Increased corrosion and erosion in piping and equipment, especially in turbines due to the impact of water droplets. Decreased overall system efficiency and performance. Methods for Measuring or Estimating Steam Quality Several methods exist for measuring or estimating steam quality: Throttling Calorimeter: This device expands a small sample of steam to a lower pressure, superheating it. By measuring the temperature and pressure after throttling, the initial steam quality can be calculated using thermodynamic principles. Separating Calorimeter: This device separates the liquid water from the steam sample. Measuring the mass of separated water and dry steam allows for direct calculation of steam quality. Estimation based on system parameters: If direct measurement is not possible, steam quality can sometimes be estimated based on boiler operating conditions, pressure drops, and heat losses in the steam distribution system. Maintaining and monitoring steam quality is crucial for ensuring efficient and reliable operation of steam systems. Processes Involving Saturated Steam: Condensation and Equipment Saturated steam's utility extends beyond its generation; understanding its behavior during phase change and the equipment required for its effective management are critical for maximizing its benefits. The process of condensation, coupled with the correct equipment selection, dictates the overall efficiency and reliability of steam-based systems. The Condensation Phenomenon Condensation is the process where saturated steam releases its latent heat and reverts to its liquid state (water). This phase transition is crucial for efficient heat transfer in many applications. The heat released during condensation, the latent heat of condensation, is the same amount of heat absorbed during vaporization at the same pressure. Mechanism of Steam Condensation Condensation occurs when saturated steam comes into contact with a surface that is at a temperature lower than its saturation temperature. The steam releases its latent heat to the surface. This heat transfer causes the steam molecules to lose kinetic energy, leading to a phase change from vapor to liquid. Tiny droplets of water form on the cold surface, coalesce, and eventually flow away due to gravity. Factors Influencing Condensation Rate Several factors influence the rate at which condensation occurs: Temperature Difference: A larger temperature difference between the steam and the surface promotes faster condensation. Surface Area: A greater surface area facilitates more heat transfer and consequently, a higher condensation rate. Surface Condition: Clean, smooth surfaces generally enhance condensation. Fouling or scale buildup hinders heat transfer and reduces the rate. Pressure: The saturation temperature of steam is directly related to pressure. Higher pressure steam condenses at a higher temperature, potentially increasing the temperature differential and condensation rate (depending on the cooling medium temperature). Presence of Non-Condensable Gases: The presence of non-condensable gases like air can impede condensation by creating a thermal barrier on the condensing surface. Efficient condensate removal is critical for sustained heat transfer performance. Equipment for Effective Steam Management Managing condensate effectively is crucial for optimizing steam system performance. Accumulation of condensate can lead to various problems, including reduced heat transfer, water hammer, and corrosion. The Role of Steam Traps Steam traps are automatic valves designed to discharge condensate, air, and other non-condensable gases from a steam system while preventing the loss of live steam. They are vital components in ensuring the efficiency and reliability of steam-based systems. Several types of steam traps exist, each with its operating principle and suitability for different applications. Types of Steam Traps and Functionality Common types of steam traps include: Thermostatic Steam Traps: These traps respond to temperature differences. They typically use a bimetallic element or a liquid-filled element that expands or contracts with temperature changes, opening or closing the valve. They are well-suited for applications where condensate temperature is close to steam temperature. Mechanical Steam Traps: These traps operate based on the difference in density between steam and condensate. Float traps and inverted bucket traps are common examples. Float traps use a float that rises with condensate level, opening the valve. Inverted bucket traps use an inverted bucket that floats in steam and sinks in condensate, actuating the valve. Thermodynamic Steam Traps: These traps rely on the thermodynamic properties of steam and condensate to operate. Disc traps are a common type, using a disc that opens and closes based on pressure and flow characteristics. The selection of the appropriate steam trap is crucial for efficient condensate removal and prevention of steam loss. Differentiating Saturated Steam from Other Steam Phases Understanding the differences between saturated steam, superheated steam, and subcooled water is essential for proper system design and operation. Saturated Steam vs. Superheated Steam Saturated steam exists in equilibrium with liquid water at its boiling point. Its temperature is solely dependent on its pressure. Adding more heat to saturated steam at constant pressure will result in superheated steam. Superheated steam is heated above its saturation temperature at a given pressure. It contains more energy than saturated steam at the same pressure and is used in applications where dry steam and high energy are required, such as in steam turbines. Superheated steam does not condense as readily as saturated steam, making it less effective for certain heat transfer applications. Saturated Steam vs. Subcooled Water Subcooled water (also known as compressed liquid) is water at a temperature below its saturation temperature at a given pressure. To form saturated steam, subcooled water must first be heated to its saturation temperature. Unlike saturated steam, subcooled water does not undergo a phase change upon a slight reduction in temperature. It requires a significant temperature increase to reach boiling point. Each phase of water – subcooled, saturated, and superheated – has distinct properties and applications, demanding careful consideration in system design. Applications of Saturated Steam: Power, Heating, and Sterilization Saturated steam is not merely a theoretical concept; it is a workhorse in diverse industries, driving critical processes with its unique thermodynamic properties. Its applications span power generation, industrial heating, commercial HVAC systems, and sterilization techniques, demonstrating its versatility and irreplaceable role. This section delves into these key applications, examining how saturated steam's characteristics are leveraged to optimize efficiency, ensure reliability, and meet stringent operational demands. Power Generation with Steam Turbines The utilization of saturated steam in power generation, particularly within steam turbines, represents a cornerstone of electricity production. Steam turbines convert the thermal energy of steam into mechanical work, which then drives generators to produce electricity. Saturated steam, due to its high latent heat of vaporization, is an efficient medium for transferring this energy. The Role of Saturated Steam In steam turbine operation, saturated steam enters the turbine at high pressure and temperature. As it expands through the turbine blades, it does work, causing the rotor to spin. The steam's energy is progressively converted into kinetic energy, which is then transformed into mechanical energy. The use of saturated steam ensures a consistent and predictable energy transfer, contributing to the stable and reliable operation of the turbine. Efficiency Considerations While saturated steam is effective for energy transfer, its use in turbines presents specific efficiency considerations. The presence of moisture in the steam, especially towards the later stages of the turbine, can lead to erosion of the turbine blades and reduced efficiency. To mitigate these issues, measures such as reheating the steam or employing moisture separation techniques are often implemented. Modern power plants are also designed to optimize steam conditions (pressure and temperature) to enhance overall cycle efficiency. Heating Systems: Industrial, Commercial, and Residential Saturated steam's high heat content makes it an ideal medium for various heating applications, ranging from large-scale industrial processes to commercial HVAC systems and even residential heating. Its ability to deliver large amounts of heat at a constant temperature, coupled with its ease of distribution and control, contributes to its widespread adoption. Saturated Steam in HVAC Systems In commercial buildings, saturated steam is often used in HVAC (Heating, Ventilation, and Air Conditioning) systems to provide space heating. Steam radiators or heat exchangers transfer the heat from the steam to the air, which is then circulated throughout the building. These systems offer rapid heating and precise temperature control, making them suitable for large or complex buildings. Advantages and Disadvantages Compared to Other Heating Methods Compared to other heating methods like hot water or forced air, saturated steam offers several advantages. It provides a higher heat transfer coefficient, allowing for smaller and more compact heat exchangers. Steam systems also respond quickly to changes in demand, providing faster heating. However, steam systems also require more careful management to prevent issues like water hammer and corrosion. They also demand specialized equipment and expertise for installation and maintenance. Safety considerations are paramount when dealing with high-pressure steam. Sterilization: The Critical Role in Autoclaves Saturated steam plays a pivotal role in sterilization processes, particularly in autoclaves, which are widely used in healthcare, pharmaceutical, and laboratory settings. The effectiveness of saturated steam as a sterilizing agent stems from its ability to deliver high heat and moisture, which are essential for killing microorganisms and denaturing proteins. Importance of Saturated Steam for Effective Sterilization Saturated steam achieves sterilization through a combination of heat and moisture. The high temperature denatures the proteins of microorganisms, rendering them inactive, while the moisture facilitates heat transfer and disrupts cellular structures. Saturated steam ensures thorough and reliable sterilization, making it a critical component in preventing infections and ensuring the safety of medical devices and laboratory equipment. Parameters for Autoclave Operation Effective autoclave operation relies on precise control of several parameters, including temperature, pressure, and exposure time. Saturated steam must be maintained at a specific temperature (typically 121°C or 134°C) and pressure to achieve the desired level of sterilization. The exposure time depends on the type of materials being sterilized and the potential for microbial contamination. Regular monitoring and validation of these parameters are essential to ensure the autoclave's effectiveness. Saturated steam exists at a temperature that corresponds directly to its pressure. Adding or removing heat will change the state (liquid or gas) rather than the temperature. Superheated steam, in contrast, has been heated beyond its saturation temperature at a given pressure. Why is saturated steam so effective for heat transfer? Saturated steam provides a large amount of latent heat, which is released when it condenses back into water. This efficient heat transfer, coupled with its constant temperature during condensation, makes what is saturated steam ideal for various heating processes. What are some common industrial applications for saturated steam? Saturated steam is widely used for power generation, sterilization in hospitals and food processing, and for heating in manufacturing processes. Its efficient and consistent heat transfer capabilities make what is saturated steam a preferred choice for these applications. How are the pressure and temperature of saturated steam related? The pressure and temperature of saturated steam have a direct and predictable relationship. Increasing the pressure also increases the temperature at which the steam will form (or condense). This relationship is key to controlling what is saturated steam in various applications. So, there you have it – a quick dive into what saturated steam is, its cool properties, and how we put it to work. Hopefully, you've got a better handle on this versatile form of water and can appreciate its role in everything from power generation to keeping your hospital equipment sterile. Pretty neat stuff, right? Vapor quality is one of the crucial parameters substantially affecting the flow boiling heat transfer coefficient. Hence, the reliability and accuracy of vapor quality measurements is of a great significance to accurately investigating the effect of vapor quality on the local flow boiling heat transfer coefficients. In the present study, various experimental approaches are represented to measure and control local vapor quality for flow boiling tests. Experimental approaches are classified based on the type of thermal boundary conditions imposed on the tube wall, that is, known constant wall heat flux and constant wall temperature (unknown variable wall heat flux). In addition, in-situ techniques are also investigated to measure local vapor quality regardless of the governing thermal boundary conditions within two-phase flow experiments. Finally, the experimental methodologies are compared based on their level of reliability and accuracy in measurement, costliness and affordability, and simplicity in execution to address their potential merits and demerits. vapor quality measurement experimental methodologies two-phase flow boiling thermal boundary conditions Vapor quality is a crucial parameter which affects the flow boiling heat transfer behavior [1, 2]. Figure 1 shows flow development inside a vertical tube under a constant wall heat flux, where the fluid moves in the upward direction. The figure also depicts various two-phase flow regimes in a vertical tube on the left and typical variations in local boiling heat transfer coefficient versus vapor quality on the right. From Figure 1, it can be inferred that flow boiling heat transfer coefficient is typically maximized in the range of vapor quality between 50% and 85%, while the smallest heat transfer coefficients tend to appear in the vapor forced convection region due to the low thermal conductivity of vapor as compared to that of the liquid. Accordingly, the accuracy of vapor quality measurements plays a significant role in properly investigating the impact of vapor quality on the local flow boiling heat transfer coefficient. On the other hand, in order to develop more efficient two-phase flow heat transfer systems, a specific range of vapor qualities should be targeted in design of thermal systems to achieve a higher range of boiling heat transfer coefficients. This also clearly highlights the significance of accurate vapor quality measurements at both the inlet and outlet of a test section.Typical variations in heat transfer coefficient with vapor quality for forced-convection flow boiling in a tube [1].Hardik and Prabhu [3] performed experiments to investigate the heat transfer and pressure drop of a diabatic two-phase water flow boiling in horizontal thin walled stainless steel tubes with different inner diameters under uniform wall heat flux conditions. To investigate the impact of vapor quality on the local boiling heat transfer coefficient, they measured vapor quality at the outlet of test section using a known range of uniform wall heat fluxes directly supplied by electrical heating tapes wrapped around the test sections. The effect of inlet vapor quality was not investigated in their study since a saturated liquid flow was provided at the inlet of test sections. In their study, the heat losses from the heating tapes were estimated using theoretical calculations of convective and radiative heat losses from the surface of test sections to the surroundings, and no single-phase experiments were conducted to empirically estimate heat losses at the same mass flux range of flow boiling tests.A similar approach to measurement of outlet vapor quality was adopted by Yan et al. in two different studies [4, 5] to investigate the influence of crucial parameters, consisting of heat flux, mass flux, and vapor quality on the heat transfer performance of water flow boiling in a uniformly heated vertical nickel alloy tube as well as in a vertical 304 stainless steel (SS304) tube with twisted tape inserted under high heat flux conditions.Although many experimental studies have been conducted to date to investigate the impact of local vapor quality on boiling heat transfer performance, majority of these studies have taken the similar approach to measure local vapor quality only at the outlet of test section mainly under uniform wall heat flux boundary conditions using electrical heating [6, 7, 8, 9, 10, 11, 12]. There are limited studies investigating the effect of local vapor quality for other thermal boundary conditions [13, 14], while their techniques to measure local vapor quality are not reported clearly. Hence, there is a considerable gap in the literature concerning vapor quality measurement under other thermal boundary conditions (e.g. uniform wall temperature and unknown boundary conditions) than the uniform wall heat flux using electrical heating.The measurement and control of local vapor quality for uniform wall heat flux conditions using heating tapes wrapped around the test section is simpler than that for uniform wall temperature or variable wall heat flux conditions where the latent heat for two-phase flow boiling is supplied by a hot-side fluid at test section. In the latter case, there is no opportunity for a direct control of vapor quality at test section unless using in-situ measurements of local density through the existing instruments with a currently low accuracy.Concerning the existing gaps in the literature addressed above, the present study aims to investigate various experimental approaches to measure and control vapor qualities at both the inlet and outlet of a typical test section under different thermal boundary conditions imposed on a test section during two-phase flow boiling heat transfer process, including uniform wall temperature, uniform wall heat flux, and unknown boundary conditions. The experimental techniques are then compared based on their level of accuracy and overall uncertainty, costliness, as well as simplicity in implementation. Advertisement Measurements of local vapor quality of a saturated boiling flow can strongly be affected by accuracy in estimating the heat losses and calibrating the latent heat supplies. This is due to the existence of latent heat during a boiling process with a constant saturation temperature of fluid while enthalpy increases with the increase of local vapor quality as a result of heat acquisition [1, 2]. This is therefore evident that inaccurate estimation of heat losses and imprecise calibration of latent heat supplies would pose unreliability in collected heat transfer data and large errors in results as well.Although different theoretical and experimental approaches have been engaged to date to estimate heat loss during flow boiling, majority of these methods are based on the estimation of heat loss from single-phase flow [6, 9, 10, 11, 12, 13, 14, 15]. Indeed, single-phase experiments were conducted to estimate heat loss percentages for a range of mass fluxes and heat fluxes. Then, the same heat loss percentages derived from the single-phase flow were directly used for two-phase flow at the same mass fluxes [6, 9, 10, 11]. Alternatively, the heat losses extracted from single-phase flow for a range of mass and heat fluxes were developed for flow boiling over another range of mass and heat fluxes using either interpolation or extrapolation [12, 13, 15].In this commonly applied methodology, the amounts of heat experimentally supplied for the test section (Qsuppl) to increase the temperature of single-phase flow from a known value of Tsp, in at the inlet to another known value of Tsp, out at the outlet are monitored and recorded for a range of flow rates. On the other hand, the actual amounts of heat transferred to the fluid Qtransf can be calculated by the following energy balance for a range of flow rates:Qtransf=m.CpTsp,out−Tsp,inE1The difference between Qsuppl and Qtransf reveals the heat losses Qloss=Qsuppl−Qtransf . A correlation is then developed by plotting the variations of heat transferred to the fluid Qtransf versus heat supplied Qsuppl, which can be used for calibrating the heat supplies as an imperative step to further measure vapor qualities within the flow boiling tests. Advertisement After estimating heat losses and calibrating heat supplies for any of electrical heater units in a test setup, local vapor qualities at the inlet and outlet of a test section can be measured by energy balance on the enthalpy change of vaporization. Figure 2 depicts the schematics of a typical setup to conduct measurements of vapor qualities under known constant wall heat flux boundary conditions using the electrical heating either through the direct resistance heating of the test tube or with the heating tapes wrapped around the tube.The experimental approach to measuring vapor qualities for uniform wall heat flux boundary conditions.As shown in Figure 2, while inlet vapor quality can be controlled using the heat-supplying unit located right before the test section (called Pre-Heater), local vapor quality at the outlet of test section may be controlled from the heat-supplying unit at the test section (called TS-Heater). The subcooled liquid at a certain pressure of Psat with a bulk temperature of Tsp is warmed up by a heat-supplying unit (i.e. SP-Heater) in order to reach the state of saturated liquid (x = 0%) at the saturation temperature of Tsat corresponding to the system pressure of Psat. Using the Pre-Heater located right before the test section, the saturated liquid therefore reaches a certain vapor quality at the inlet of the test section (xin) and is afterwards exposed to a known constant wall heat flux supplied by the TS-Heater at the test section to reach a two-phase flow of higher vapor quality at the outlet (xout), and then keeps recirculated.To ensure the state of saturated liquid, the subcooled liquid is warmed up by the SP-Heater to reach a temperature infinitesimally lower than the saturation temperature of Tsat targeted for the flow boiling experiments. Using the sight glass shown in Figure 2, the state of saturated liquid is also directly observed in order to check whether or not there is any vapor bubble in the saturated liquid flow.As represented in Figure 2, the inlet vapor quality is measured and controlled by adjusting the calibrated heat supplied by the Pre-Heater to take the saturated liquid (x = 0) to the two-phase flow with a desired inlet quality of xin as follows:Qcalib−pre=Qsuppl−pre−Qloss−pre=m.hxin−hfx=0E2where hx accounts for the enthalpy at vapor quality of x, Qsuppl:pre is the heat experimentally supplied by the Pre-Heater, Qloss−pre is the corresponding heat loss from this heat-supplying unit, and Qcalib−pre stands for the calibrated heat which is actually transferred to the boiling flow. Having the enthalpy of saturated liquid (hf (x=0)) known, the only unknown parameter in Eq. (2) is the enthalpy at the inlet of the test section from which the inlet vapor quality can simply be derived at the operating saturation temperature and pressure.After having the inlet vapor quality known, the outlet vapor quality can be measured from the calibrated heat at the test section (TS-Heater) as follows:Qcalib−ts=Qsuppl−ts−Qloss−ts=m.hxout−hxinE3where Qsuppl−ts is the heat experimentally supplied by the heating unit at the test section, Qloss−ts is the corresponding heat loss from this heat-supplying unit, and Qcalib−tsstands for the calibrated heat which is actually transferred to the boiling flow. Having the inlet quality already measured, the only unknown parameter in Eq. (3) is the enthalpy at the outlet of the test section (hxout) from which the outlet vapor quality can be extracted at the operating saturation temperature and pressure.This is important to point out that the outlet vapor quality derived from the test section contains an accumulated error arisen from earlier measurement of the inlet vapor quality. As clearly shown in Eq. (2), the inlet vapor quality can be measured and controlled by obtaining the enthalpy at the inlet of test section (hxin), which contains the uncertainties in measurement of mass flow rate (m.), bulk fluid temperature (Tsat), and calibrated heat supplies by the Pre-Heater (Qcalib−pre). This measured value of inlet vapor quality (hxin) is used as a known parameter in Eq. (3) to obtain the vapor quality at the outlet of test section (hxout). The measured value of outlet vapor quality, in turn, contains uncertainties in measurement of bulk fluid temperature and calibrated heat supplies by the test section heater (Qsuppl−ts) in addition to the earlier measurement error imposed by the value of inlet vapor quality, which eventually leads to the accumulation of more errors in measurement of outlet vapor quality through Eq. (3) as compared to that of inlet vapor quality. Advertisement In the case of constant wall temperature boundary conditions for the test section, the wall heat flux is subject to change. The measurement and control of local vapor quality at the outlet of a test section under uniform wall temperature boundary conditions is more challenging than that of uniform wall heat flux boundary conditions. In a single loop of internal flow boiling, the outlet vapor quality is typically measured and controlled by directly monitoring the constant amounts of surface heat flux provided by heating tapes wrapped around the test section. However, the use of hot fluid heating rather than electrical heating to generate constant wall temperature conditions does not allow the direct control of outlet vapor quality due to the unknown variable surface heat flux exchanged between the hot-side fluid (e.g. external condensation of steam or single-phase hot liquid) and the cold-side fluid (i.e. internal flow boiling).Figure 3 illustrates a typical case of constant temperature boundary conditions imposed by external condensation of steam on the test tube. The test section shown in this case is the place where external condensation and internal flow boiling occur simultaneously. The test section therefore functions as a cross flow heat exchanger whose both sides are manipulated with phase-change heat transfer processes. The test apparatus for this arrangement is to consist of two closed loops, including: external condensation loop (i.e. steam condensation over a horizontal tube) and internal boiling loop (i.e. two-phase flow boiling inside the tube).The experimental approach to measuring vapor qualities for uniform wall temperature boundary conditions.Within the external condensation loop, saturated vapor of water at saturation temperature and pressure of Tsat,steam and Psat,steam is provided by a steam generator and then enters the test chamber. After condensation of steam on the horizontal test tube due to the temperature difference between the saturated vapor and the tube surface (called subcooling), the condensate is driven by gravity and collected in a condensate reservoir to feed the steam generator and set a steady flow circulation in the external condensation loop. Regarding the internal boiling loop, the fluid is warmed up by the SP-Heater in order to reach the saturated liquid state (x = 0) at the saturation temperature and pressure of Tsat and Psat, respectively (Tsat < Tsat,steam). Using the Pre-Heater located right before the test section, the saturated liquid therefore reaches a certain vapor quality at the inlet of the test section (xin) and is afterwards exposed to the latent heat released from the external condensation side to reach an unknown higher vapor quality at the outlet (xout).The unknown outlet vapor quality can be measured by adding a calibrated heat-supplying unit (After-Heater) with power controller installed right after the test section in order to take the two-phase flow with unknown outlet quality to the known state of saturated vapor (i.e. x = 100%) at the same saturation temperature of Tsat. In this case, the energy balance is dictated as follows:Qcalib−after=Qsuppl−after−Qloss−after=m.hgx=1−hxoutE4where Qsuppl−after stands for the heat experimentally supplied by the After-Heater, Qloss−after is the corresponding heat loss from this heat-supplying unit, and Qcalib−afteraccounts for the calibrated heat which is actually transferred to the boiling flow. Having the enthalpy of saturated vapor (hg (x=1)) known, the only unknown parameter in Eq. (4) is the enthalpy at the outlet of the test section (hxout) from which the outlet vapor quality can be extracted at the operating saturation temperature and pressure. Similar to the case of constant wall heat flux boundary conditions stated earlier, the inlet vapor quality can independently be measured and controlled by adjusting the calibrated heat supplied by the Pre-Heater using the Eq. (2).In this approach, to ensure the state of saturated vapor, the After-Heater located after the test section is adjusted to supply the required latent heat for the two-phase flow with a certain outlet quality to reach a temperature slightly higher than the constant saturation temperature, which would be the starting point of the superheated vapor state. As shown in Figure 3, using the sight glass installed after the After-Heater, the state of saturated vapor is also directly observed in order to check whether or not there is any liquid droplet and/or humidity in the gas stream at the beginning of superheated state. Unlike the earlier approach to measuring local vapor quality at the outlet of test section under uniform wall heat flux conditions, this approach does not contain any accumulated errors arising from earlier measurements of inlet vapor qualities.In the second methodology for variable wall heat flux conditions, a tube-in-tube or shell-and-tube heat exchanger installed at the test section may be used for measuring and controlling local vapor quality at the outlet of test tube. Analogous to the earlier cases, the inlet vapor quality is measured and controlled by monitoring the calibrated heat supplied by the Pre-Heater using the Eq. (2).As represented in Figure 4, a hot liquid single-phase flow with known mass flow rates and known temperatures and pressures at the inlet and outlet passes through the outer tube (shell side), while the boiling flow of a known inlet vapor quality with a saturation temperature (Tsat) lower than that of the heating liquid (Th) enters the inner tube of the counter-flow heat exchanger. After latent heat acquisition from the hot-side fluid, the internal boiling flow undergoes an unknown increase in vapor quality at the outlet of test tube whereas the heating liquid in the shell side experiences a temperature reduction as a result of sensible heat rejection yet its temperature at the outlet remains higher than the constant saturation temperature of internal boiling flow. The vapor quality at the outlet of the test tube can therefore be controlled by adjusting the mass flow rate of the hot liquid single-phase flowmh at the shell side of the counter-flow heat exchanger.The experimental approach to measuring vapor qualities for variable wall heat flux boundary conditions.The amounts of heat exchanged between the internal boiling flow and the heating liquid can be measured by writing down an energy balance as follows:Qrejected=mh.CpTh,in−Th,out=Qgained=m.hxout−hxinE5Aside from hxout, all the other parameters in Eq. (5) are known. The enthalpy at the outlet of the test section (hxout) can thus be calculated and the vapor quality at the outlet of the test tube can be measured and controlled subsequently. Similar to the approach engaged to the uniform wall heat flux boundary conditions, the outlet vapor quality derived from this approach contains an accumulated error arisen from earlier measurement of the inlet vapor quality.To keep the boiling fluid recirculated, this is evident that other components are required for the internal boiling loop, which are not shown in Figures 2–4. Subsequent to the test section or the After-Heater, the two-phase flow with a certain outlet quality or the saturated vapor is required to be condensed in a heat exchanger to reach the state of saturated liquid which is followed by a drop in temperature and pressure after passing through an expansion valve to reach the state of subcooled liquid prior to entering the pump in order to avoid the cavitation phenomenon. The liquid flow is then squeezed by a gear pump up to the desired saturation pressure to enter the SP-Heater. Advertisement Regardless of the type of thermal boundary conditions governed on the test section, the local vapor quality of a two-phase flow boiling may be obtained through in-situ measurements.Using the experimental approaches and/or instruments introduced here, first, the local density of two-phase flow at either of the inlet or outlet of a test section can be measured in-situ for any thermal boundary conditions that might be imposed on the test section. After obtaining the density, two independent thermodynamic properties of the flow at either inlet or outlet are known (i.e. density and either of saturation temperature or corresponding pressure) in order to look up the enthalpy of the two-phase flow at either inlet or outlet (hxin or hxout). Having the local enthalpies known, the local vapor quality (x) can be readily obtained via hx=hfx=0+xhfg as the only unknown parameter left here. However, this is important to note that the accuracy of this approach is lower than those of the earlier approaches described so far in the present study due to the less accuracy of the limited experimental methodologies [16] and instruments [17, 18, 19] introduced to date to measure density of a two-phase flow.Interest in the determination of two-phase flow density has brought about the design and development of various instruments to measure density in cryogenic flow systems. The more promising of the methods suggested are based on either (i) measurements of the average dielectric constant or capacitance of the two-phase fluid or (ii) measurements of the nuclear radiation attenuation properties of the two-phase fluid. In principle, both of these measurable quantities are associated with the fluid density.Turney and Snyder [17] used a capacitance density meter to measure the density of liquid and two-phase hydrogen flow. Most of their measured and calculated values of density exhibited a deviation up to ±15% of the full-scale density. The advanced Coriolis meters have also been investigated for measurement of two-phase flow density [18, 19]. In this context, Reizner [18] has addressed the issues concerned to metering two-phase flow using the Coriolis meters. Technically, this is hard to retain flow-tube oscillations within two-phase flow due to the high and rapid damping of oscillations which is, by far, up to three orders of magnitude higher than that of the single-phase flow. Once the transmitter is not capable of maintaining the oscillations, the Coriolis meter is found to be "stalled", and no measurements are provided. Even in the case of averting the stalling, large errors in measurements of mass flow and density are induced.Although there is no specific instrument to accurately measure density of a two-phase flow, the technique(s) recently introduced by Boltenko [16] can measure the density with a reasonable accuracy. The range of uncertainty reported for his technique(s) is between 3% and 5%.The following is a brief explanation of the proposed techniques to measure local density of a two-phase flow:Gamma-raying Technique: The method of Gamma-raying makes it possible to measure density of a two-phase flow both in steady and transient flow regimes as well as makes it possible to carry out ongoing record of ρ(t) with averaging over the time intervals which are remarkably shorter than the typical duration of an unsteady process (τ > 0.1 s) [20].Hydrostatic Technique: The hydrostatic method to determine the density of a two-phase flow is performed by the measurement of static pressures at two points of a channel. After measuring the static pressure difference between these two pressure tapping points, the average density of the two-phase flow can be obtained by the following correlation [21]:in which g is the gravitational acceleration, H is the pipe diameter, ΔPhyd accounts for the hydraulic resistance between the pressure tap points, and ΔPst stands for the hydrostatic pressure difference between the pressure tap points.As can be seen from Eq. (6), it is possible to obtain ρ¯ only if ΔPhyd is known. Hence, the hydrostatic technique may be employed to measure ρ¯ for test sections with horizontal orientation. In the case of horizontal test tube ΔPhyd = 0, and then Eq. (6) reduces to:Figure 5 depicts schematics of the hydrostatic technique to measure the average density of a two-phase flow in a horizontal pipe.Schematic of the hydrostatic method to determine density of a two-phase flow [16]. Advertisement In this section, the experimental approaches are sought to be compared based on their level of accuracy in measurement, affordability, and simplicity in implementation. Remarks, including merits and demerits, are expressed for each experimental technique described in the earlier sections in sequence.The approach described in Section 3 is restricted to the investigation of the impact of local vapor quality on the heat transfer performance under known constant wall heat flux boundary conditions. Although the method is very affordable and simple to be implemented, accuracy of this methodology to measure local vapor quality is reliant heavily on the accuracy in estimating heat losses and calibrating heat supplies. Furthermore, it is important to note that the measurement of local vapor quality at the outlet of test section using this technique contains an accumulated error arisen from earlier measurement of local vapor quality at the inlet according to Eq. (3).On the other hand, the measurement of flow boiling heat transfer data for horizontal test tubes using electrical heating has always been a subject of debate [22], where hot fluid heating is preferred to be used. In this regard, the following concerns are needed to be addressed: (i) for different types of stratified flow pattern, hot fluid heating induces practically uniform wall temperature boundary conditions for the tube perimeter, whereas electrical heating contributes to the circumferential heat conduction for the tube perimeter from the hot, dry-wall conditions at the top to the colder, wet-wall conditions at the bottom of the tube, leading to unknown thermal boundary conditions, (ii) for annular flow pattern with partial dryout at the top of the tube, electrical heating is not also advised due to the axial heat conduction along the tube.Using the approach I described in Section 4.1, higher accuracy and lower uncertainty in vapor quality measurements can be achieved by conducting accurate estimation of heat losses as well as accurate calibration of heat supplies. Furthermore, measurement of local vapor quality at the outlet of test section using this technique does not contain any accumulated errors arising from earlier measurements of inlet vapor quality as represented in Eq. (4). This is while the approach is very affordable and simple in execution.Taking advantage of the After-Heater located after the test section, this technique does not interfere with heat transfer data collected from the test section and does not pose the issues of circumferential and axial heat conduction caused by electrical heating for stratified and annular flow patterns within the test section.The approach II described in Section 4.2 is more expensive than the earlier techniques presented. The method is also not as simple as the earlier techniques in implementation. Using this approach, there is still accumulated error in measurement of outlet vapor quality arisen from the earlier measurement of inlet vapor quality, according to Eq. (5).Moreover, the main drawback is that the methodology is likely to pose a higher overall uncertainty in measuring the local vapor qualities as compared to the earlier techniques described in Sections 3 and 4.1 since there will be higher number of points to be measured for temperature, pressure, and mass flow rate as indicated in Eq. (5). In this technique, five more precision instruments are required to be in service in order to measure flow rate of the hot-side fluid (one flow sensor), pressures (two pressure transducers), and temperatures (two thermocouple probes) at the inlet and outlet of the shell side of heat exchanger.The major drawback of the in-situ measurements is that the techniques and/or instruments introduced to date pose a low accuracy to measure local density of a two-phase flow, which ultimately makes the overall uncertainty for vapor quality measurements undesirable. In addition, very accurate and expensive pressure transducers and/or expensive advanced Coriolis meters are required to be procured to implement this technique properly. Vapor quality plays a key role in flow boiling heat transfer behavior and can noticeably affect the local flow boiling heat transfer coefficient. To accurately investigate the effect of vapor quality on flow boiling behavior, accurate measurement of local vapor quality is critical.In the present study, various experimental techniques were presented to measure and control vapor quality for flow boiling tests and were classified based on the type of thermal boundary conditions induced on the test tube wall. Moreover, in-situ measurements and techniques were also investigated to measure local density of two-phase flow and subsequently local vapor quality regardless of the governing thermal boundary conditions.To provide a deeper insight to select an appropriate technique depending on researchers' choices, the experimental techniques were also compared based on their level of accuracy in measurement, affordability, and simplicity in implementation through addressing their potential weaknesses and strengths. We would like to acknowledge the financial support from NASA MUREP Institutional Research Opportunity Grant under Cooperative Agreement #80NSSC19M0196, National Science Foundation (NSF) for supporting this work via grant (HRD-1601156), and Department of Defense under contract: W911NF-20-1-0274. 1. Bergman T.A., Levine A.S., Incropera F.P., Dewitt D.P., Fundamentals of Heat and Mass Transfer, John Wiley & Sons Inc., 7th Edition, 2011, ISBN 13 978-0470-50197-9.2. 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Fedorov L.F., Rassokhin N.G., Processes of Steam Generation at Nuclear Power Plants, Ener_goatomizdat, 1985, Moscow, in Russian.22. Thome J.R., The Heat Transfer Engineering Data Book III, PP PUBLICO Publications, 2016, ISBN-13: 9783934736375. Submitted: 27 July 2020 Reviewed: 13 October 2020 Published: 16 November 2020 See also: Properties of SteamAs seen from the phase diagram of water, in the two-phase regions (e.g.,, on the border of vapor/liquid phases), specifying temperature alone will set the pressure, and specifying pressure will set the temperature. But these parameters will not define the volume and enthalpy because we will need to know the relative proportion of the two phases present.The mass fraction of the vapor in a two-phase liquid-vapor region is called the vapor quality (or dryness fraction), x, and it is given by the following formula:The value of the quality ranges from zero to unity. Although defined as a ratio, the quality is frequently given as a percentage. From this point of view, we distinguish between three basic types of steam. It must be added, at x=0, we are talking about the saturated liquid state (single-phase).Wet SteamDry SteamSuperheated SteamThis classification of steam has its limitation. Consider the system's behavior which is heated at a pressure that is higher than the critical pressure. In this case, there would be no change in phase from liquid to steam. In all states, there would be only one phase. Vaporization and condensation can occur only when the pressure is less than the critical pressure. The terms liquid and vapor tend to lose their significance.See also: Saturation.See also: Throttling of Steam