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Feasibility Study of an Integrated Sensor System for Measurement of Phase and Temperature Distribution

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1. Introduction

Two-phase flow frequently occurs in industrial thermal systems such as heat exchangers, boilers, and gas pipelines. In such environments, real-time and accurate measurement of both phase and temperature distributions is essential for system safety, operational stability, and energy efficiency optimization. While various sensing technologies have been developed to monitor each parameter independently, conventional approaches typically employ separate sensor systems, resulting in issues such as spatial and temporal misalignment of measured data and physical constraints on sensor installation. To address these challenges, this study proposes and experimentally validates an integrated sensor system that enables co-located measurement of phase and temperature within a single device under two-phase flow conditions. The core concept is based on modifying a conventional Wire-Mesh Sensor (WMS) by replacing its wire electrodes with stainless steel (STS) tubes embedded with Optical Fiber Sensor (OFS). This combination of electrical and optical sensing techniques allows the sensor to capture electrical conductivity data for phase detection and distributed temperature data at the same spatial locations [1,2].

The WMS component operates on the principle of detecting the local conductivity between crossing electrodes in the mesh. When an electrical voltage is applied to a set of transmitter electrodes, the current received by orthogonal receiver electrodes varies depending on the conductivity of the medium—liquid phase offering higher conductivity and gas phase significantly lower. By scanning across the mesh, the WMS200 system reconstructs a two-dimensional phase distribution map. The OFS used in this study measures temperature based on Rayleigh backscattering and enables continuous temperature acquisition along the entire length of the fiber. This is because subtle changes in the fiber's physical properties along its length cause variations in the backscattered light, which are then precisely detected and analyzed by an Optical Frequency Domain Reflectometry (OFDR) system. This process allows the system to detect signal changes at each location along the fiber, enabling real-time, high-resolution temperature measurement across the entire sensing region. The ODiSI 6000 system is employed, which offers a maximum spatial resolution of 0.65 mm.

By combining these two techniques into a single device, the sensor system enables co-located measurement of thermal and flow parameters, improving the spatial and temporal correlation of data. This compact and integrated configuration is particularly advantageous in confined environments, and its ability to capture localized heat transfer characteristics makes it a promising tool for enhancing the accuracy of two-phase flow analysis and supporting real-time diagnostics in industrial thermal-fluid systems.

2. Design Device

The objective of this study is to design and fabricate an integrated sensor system capable of measuring phase and temperature distributions within a single device. The proposed sensor modifies the conventional WMS by replacing its wire electrodes with electrically conductive STS tubes (Ø 0.4 mm) embedded with distributed OFS (Ø 0.155 mm). These tubes are arranged orthogonally in vertical and horizontal directions to form a 15×15 mesh structure, enabling both conductivity-based phase detection and optical temperature measurement at the same spatial locations.

Several key design considerations were addressed during development. First, uniform tensioning of each STS tube was essential to ensure precise spacing between tubes, directly affecting the reliability of phase distribution measurements. Turnbuckles were employed to apply consistent and repeatable tensile forces, and their length served as a reference to achieve uniform tension across the entire mesh. Second, integration of mechanical fixation and electrical signal transmission was realized by utilizing the PCB as both a structural support and an interface for signal input/output. Each tube is mechanically fixed to the PCB, which also houses the conductive pathways for voltage application and signal reception. This design minimized the number of components and assembly complexity. Third, supporting structures were added to ensure secure connection to the two-phase flow experiment system, prevent leakage, and protect the optical fibers. The bottom of flange was machined to match the outer diameter of the tubes, securing them in place and sealing the interface. An OFS bracket was mounted between the PCB and the flange to protect the fibers from external impacts and environmental changes.

Regarding sensor resolutions, the Optical Fiber Sensor (OFS) provides a spatial resolution of 0.65 mm and operates with a temporal sampling rate of 15.61 Hz, enabling high-resolution and real-time temperature measurements along the fiber length. The Wire-Mesh Sensor (WMS) features a mesh spacing of 4.5 mm between the STS tubes, which defines its spatial resolution for phase detection. This spacing determines the smallest distinguishable spatial features in the phase distribution map. Hence, the integrated system leverages the fine spatial and temporal resolution of the OFS for temperature sensing, while the WMS offers reliable, conductivity-based phase detection with moderate spatial resolution constrained by mesh geometry.

The complete device adopts a monolithic structure for simultaneous sensing of phase and temperature distributions. The sensor circuitry was designed to be compatible with the WMS200 system, incorporating D-sub connectors for external connection and routing electrical signals through the printed circuit board (PCB). During assembly, copper wires were looped through the PCB soldering holes and around the STS tubes, then pulled taut from beneath to hold the tubes in position. The opposite tube ends were secured in the same manner using a separate support plate. Uniform tension was applied using turnbuckles to maintain alignment and structural stability. The final assembly steps included flange mounting, D-sub soldering, optical fiber insertion, and bracket installation. The overall structure of the sensor system is illustrated in Fig. 1. Through this design, the proposed integrated sensor system successfully combines electrical and optical sensing capabilities within a unified structure, addressing both measurement reliability and mechanical stability for application in multiphase flow experiments [1].

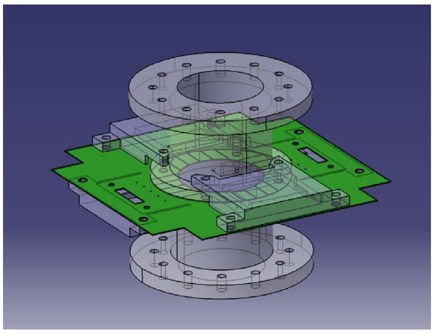

Fig. 1. Overall structure of the integrated sensor device

3. Concept Validation Experiment

To evaluate the measurement performance of the proposed integrated sensor system, an experimental setup was designed and constructed to simulate a two-phase flow environment in a vertical pipe. As shown in Fig. 2, the system consists of a vertical acrylic pipe with an inner diameter of approximately 100 mm, along with a water circulation system, a gas injection unit for generating bubbles, and heaters to impose a controlled temperature gradient. Water is supplied from a chiller to the bottom of the test section, flows upward through the vertical pipe, and is returned to the chiller from the top outlet, completing a continuous circulation loop. Air is introduced through an external compressed air supply line, which includes a pressure regulator capable of adjusting the pressure up to 0.3 MPa. At the bottom of the flow pipe, three needle tubes are installed, each equipped with an independent valve for precise control of bubble injection. The injected air forms bubbles that rise through the pipe and are discharged at the top outlet. In addition, cartridge heaters are installed at the bottom of the pipe to establish a vertical temperature gradient. The fabricated integrated sensor device is installed 1,000 mm above the bottom of the pipe, with a total sensor device height of approximately 200 mm.

The sensor forms a 15×15 mesh structure, consisting of 225 crossing points where electrodes and optical fibers are embedded. This configuration enables measurement of phase and temperature distributions at the same spatial locations within the two-phase flow. Phase distribution is measured using a WMS200 system, which continuously monitors the electrical conductivity between electrodes. Because gas has significantly lower conductivity than liquid, the system can effectively distinguish between the two phases based on localized conductivity differences across the mesh. Temperature distribution is measured using a LUNA ODiSi distributed optical fiber sensing system, which is based on Rayleigh backscattering. The sensor detects frequency shifts caused by temperature-induced variations in the fiber's refractive index. Using the OFDR principle, the system allows for spatially resolved temperature measurements along the fiber with a maximum spatial resolution of 0.65 mm. This experimental setup allows independent control of temperature gradients and bubble injection conditions, providing a flexible environment for assessing the integrated sensor system's capability to simultaneously monitor phase and temperature distributions under various flow scenarios [3,4].

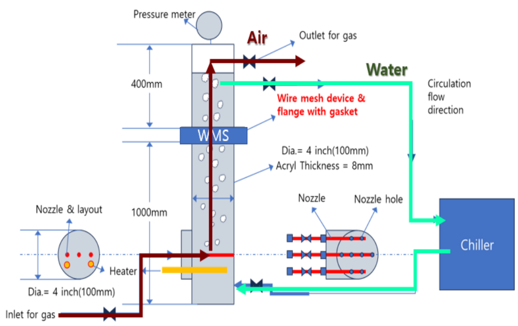

Fig. 2. Schematic diagram of the experimental two-phase flow system

3.1. Temperature Measurement Validation

To evaluate whether the integrated optical fiber sensor within the proposed hybrid sensor system can effectively detect temperature changes under thermal gradient conditions, a temperature validation experiment was conducted as follows. The chiller was operated to circulate water until the fluid temperature stabilized at 20 °C. Then, a cartridge heater installed at the bottom of the vertical pipe was activated with a setpoint temperature of 50 °C. The experiment was terminated when the distributed optical fiber sensor detected a temperature rise exceeding 5 °C across the mesh region, which occurred approximately one hour after heating began.

After heating with the cartridge heater, temperature were monitored, and data corresponding to the point at which the overall temperature had increased by approximately 5 °C compared to the initial condition were selected for analysis. The raw temperature data from the distributed optical fiber sensor were post-processed using MATLAB R2025a to visualize the spatial temperature distribution across the sensor mesh. First, the spatial coordinates of each sensor intersection point within the 15×15 mesh were defined. The temperature values were subsequently interpolated across the domain using cubic interpolation techniques to generate a continuous two-dimensional(2D) temperature distribution map. As shown in Fig. 3, the 2D temperature distribution clearly reveals localized thermal gradients near the heater location. Notably, asymmetric spreading of heat was observed along the flow direction of the circulating water, resulting in a non-uniform temperature profile across the mesh. This phenomenon highlights the influence of convective transport within the vertical pipe and confirms that the optical fiber sensor can measure spatial temperature variations. The results demonstrate that the proposed sensor system is capable of capturing temperature differences and thermal behavior in two-phase flow environments [5].

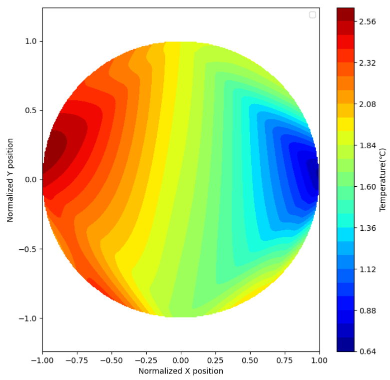

Fig. 3. 2D temperature distribution across the mesh measured by OFS

3.2. Phase Distribution Measurement Validation

This experiment aimed to evaluate the capability of the fabricated integrated sensor system to measure phase distribution. After circulating water at 20 °C in the test loop, air was injected at the bottom of the flow pipe for approximately 3 s. The measurement data collected before and after air injection were analyzed to assess the sensor's ability to detect phase changes.

Since the WMS200 system is designed for a 16×16 mesh structure, and the developed sensor utilizes a 15×15 mesh configuration, a data processing step was conducted to exclude positions without actual electrodes. Rows and columns with consistently zero readings over time were identified and removed, resulting in a 15×15 dataset corresponding to the physical sensor mesh. The average conductivity value at each mesh intersection during the injection period was calculated and visualized as a two-dimensional image using MATLAB R2025a. Fig.4 and 5 present the measured phase distributions when the device was tilted toward the 6 o'clock and 9 o'clock orientations, respectively. In both cases, regions occupied by liquid exhibited relatively high electrical conductivity and thus appeared as darker areas in the reconstructed images, whereas gas-dominated regions showed low conductivity and appeared with lighter or no color. These results clearly demonstrate that the integrated sensor system can effectively capture the influence of device inclination on two-phase flow behavior, providing a distinct separation between liquid and gas phases. Moreover, the observable shift in phase distribution with tilt angle confirms the capability of the proposed sensor to accurately track local phase dynamics under varying flow conditions.

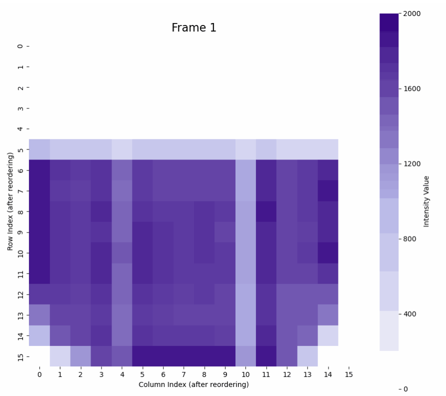

Fig. 4. 2D Phase distribution measured by WMS when the device was tilted toward the 6 o'clock orientation

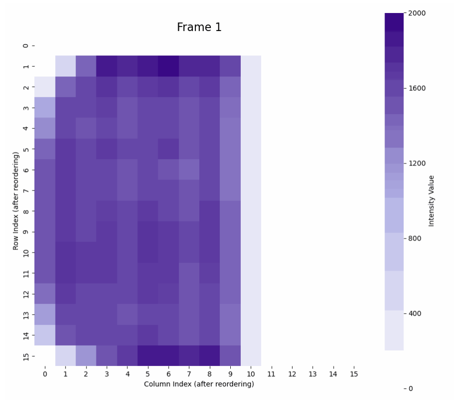

Fig. 5. 2D Phase distribution measured by WMS when the device was tilted toward the 9 o'clock orientation

4. Conclusion

This study proposed and experimentally validated an integrated sensor system that replaces the wire electrodes of a conventional WMS with STS tubes embedded with a distributed OFS. The resulting configuration enables co-located measurement of phase and temperature distributions within a single device. The concept was evaluated through experiments conducted in a vertical pipe system simulating two-phase flow conditions. The experimental results demonstrated that the sensor successfully captured the temperature gradient induced by a cartridge heater, confirming its capability for distributed temperature measurement. However, the phase distribution measurement was limited due to grounding issues in the circuit design, which prevented stable signal acquisition. This highlighted the need for improved electrical grounding compatibility with the WMS200 system. Future work will focus on redesigning the circuit to ensure a common ground reference with the WMS200, followed by re-evaluation of phase detection performance. Additionally, experiments will be extended to conditions where both phase and temperature variations occur simultaneously, enabling full validation of the sensor's dual-function capability. The proposed sensor system offers a unique advantage by providing both phase and temperature information at the same spatial locations through a single compact device. This capability is expected to improve the accuracy of multiphase flow diagnostics and enhance measurement efficiency in complex industrial environments.

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