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Cavitation Phenomena in Cryogenic Pumps for Liquid Methane Applications

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Abstract— **Cavitation is a critical fluid dynamic phenomenon that leads to performance loss, efficiency reduction, and long-term reliability issues in pumps operating under cryogenic conditions. Conventional cavitation assessment methods based on Net Positive Suction Head (NPSH) are limited in capturing the thermodynamic effects present in cryogenic environments. This study addresses this limitation through a pressure–temperature (P–T) dependent two-phase thermodynamic model, developed to dynamically analyze the cavitation behavior of a cryogenic centrifugal pump operating with liquid methane using the MATLAB/Simulink/Simscape environment. The thermodynamic and thermophysical properties of methane were defined using tabulated data and empirical correlations reported in the literature, ensuring accurate representation of phase-dependent behavior. Several scenario-based simulations were conducted under different inlet pressure and temperature conditions to examine the pump's performance characteristics. The model evaluated variations in pressure, temperature, flow rate, and vapor quality at both the pump inlet and outlet. The results indicate that as vapor quality increases, pressure fluctuations and flow instabilities become more pronounced, leading to a noticeable decline in pump performance. The findings reveal that cavitation in cryogenic pumps is not only a thermodynamic process but also a dynamic instability that significantly affects hydrodynamic stability. This study provides valuable insights for predicting and mitigating cavitation in cryogenic fluid systems and contributes to the development of more robust and efficient cryogenic pump process designs.**

Keywords— **Cavitation phenomenon, cryogenic fluids, liquid methane, dynamic modeling, two-phase flow, vapor quality**

I. INTRODUCTION

Cryogenic centrifugal pumps operating with liquid methane are critical components in various energy and process engineering applications. In the liquefied natural gas (LNG) industry, they are widely used for the transfer, pressurization, and vaporization of methane during storage, regasification, and fuel supply operations. These pumps are also employed in liquefied compressed natural gas (LCNG) and cryogenic fueling stations, where they ensure stable delivery of methane to vehicle dispensers at controlled pressures. In industrial and aerospace sectors, liquid methane serves as both a cryogenic working fluid and a propellant, requiring reliable pump operation under extremely low temperatures to prevent vapor lock or flow interruption. Due to the low boiling point and high volatility of methane, maintaining consistent suction conditions and preventing cavitation are essential for ensuring efficiency, safety, and long-term reliability of these systems. Consequently, understanding and modeling the dynamic cavitation behavior of methane in centrifugal pumps are of significant importance for the design and optimization of next-generation cryogenic fluid handling systems.

Cavitation in cryogenic fluids, such as liquid methane, takes place when the local pressure–temperature state crosses the saturation curve; that is, when the local pressure becomes lower than the saturation vapor pressure corresponding to the prevailing temperature, leading to the onset of vapor nucleation (the initial formation of microscopic vapor bubbles within the liquid). Compared to room-temperature liquids, cryogenic fluids exhibit low viscosity, high compressibility, and a narrow margin between operating and vapor pressures, which increases their sensitivity to pressure and temperature fluctuations. As vaporization locally absorbs latent heat, the resulting temperature drop alters the vapor–liquid equilibrium, making cavitation behavior strongly dependent on both fluid dynamic and thermodynamic effects. Hosangadi et al. [1] demonstrated through numerical simulations that variations in density, viscosity, and vapor pressure significantly influence bubble dynamics in cryogenic fluids, while Li et al. [2] highlighted the combined effects of thermodynamic suppression and local cooling that distinguish cryogenic cavitation from classical isothermal forms.

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In practical pump design, cavitation is often assessed through the Net Positive Suction Head (NPSH) criterion, which defines the pressure margin above the vapor pressure at the pump inlet. However, in cryogenic systems, where fluid properties vary strongly with temperature, cavitation can be more accurately characterized using the pressure–temperature (P–T) equilibrium relationships that govern phase transition. This thermodynamic approach forms the foundation of the present study.

This study aims to dynamically model and analyze the performance behavior of a cryogenic centrifugal pump operating with liquid methane under both normal and cavitating conditions in MATLAB/Simulink/Simscape. The thermophysical property data of liquid methane, including density, viscosity, enthalpy, entropy, thermal conductivity, and specific heat capacity, were derived from established equations of state and verified thermodynamic correlations available in the literature. These tabulated values were used to define the Two-Phase Fluid Properties block parameters in MATLAB/Simscape, ensuring accurate representation of phase-dependent behavior under varying temperature and pressure conditions. The simulation system consists of inlet reservoir, suction pipe, centrifugal pump, discharge pipe, chamber components and outlet reservoir, representing the suction, impeller, and discharge sections of the cryogenic pump, respectively. Real-time virtual sensors were implemented to monitor inlet and outlet parameters such as pressure, temperature, flow rate, and vapor quality, allowing direct observation of phase transitions and bubble formation. Several scenario-based simulations were conducted under different inlet pressure and temperature conditions. The results demonstrated that as vapor quality increased, vapor bubbles expanded, the flow became unstable, and pump performance declined. This dynamic model provides a quantitative framework for understanding cavitation mechanisms in cryogenic environments and offers valuable insights for developing advanced cavitation prevention and early detection strategies in cryogenic pump systems.

II. Simulation Modeling

A dynamic two-phase flow model was developed to simulate cavitation behavior in a cryogenic centrifugal pump using MATLAB/Simulink/Simscape.

A. Model Overview

Figure 1 illustrates the overall Simscape-based dynamic model developed to simulate cavitation behavior in a cryogenic centrifugal pump operating with liquid methane. The model comprises inlet reservoir, suction pipe, centrifugal pump, discharge pipe, chamber components and outlet reservoir, which represent the suction, impeller, and discharge sections of the cryogenic pump, respectively. The simulation is based on a pressure–temperature (P–T) dependent two-phase thermodynamic approach, rather than the traditional Net Positive Suction Head (NPSH) criterion, allowing the direct evaluation of phase transition phenomena under varying inlet pressure and temperature conditions. The model performs a time-dependent dynamic analysis to capture transient variations in pressure, temperature, vapor quality, and mass flow rate during both stable and cavitating operation modes, providing a physically consistent representation of cryogenic pump performance.

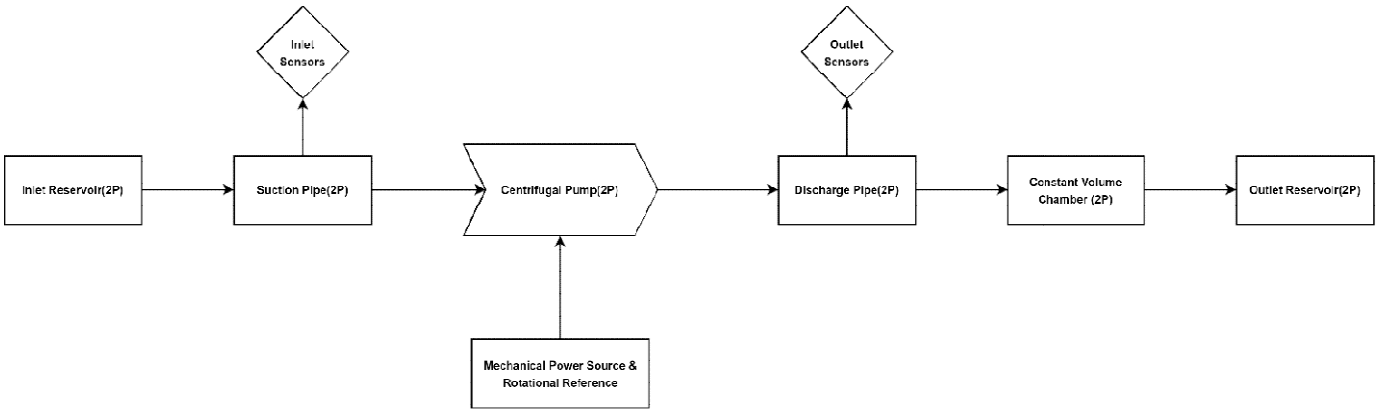

Fig. 1 Block diagram representation of the developed cryogenic pump model implemented in MATLAB/Simulink/Simcape environment

B. Two-Phase Fluid Properties Definition

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The thermophysical properties of methane were defined in the Two-Phase Fluid Properties (2P) block using tabulated data obtained from the National Institute of Standards and Technology Reference Fluid Thermodynamic and Transport Properties Database (NIST REFPROP, Version 10.0) [3]. The property dataset was primarily based on the equation of state developed by Span and Wagner [4], and validated against experimental data and correlations reported by McLinden et al. [5]. The property tables covered a pressure range of 1–5 bar and a temperature range of approximately –162 °C to –137 °C, corresponding to cryogenic operating conditions. Key parameters, including density, internal energy, entropy, thermal conductivity, kinematic viscosity, and Prandtl number, were extracted for both liquid and vapor phases to ensure accurate phase-dependent representation. Each property was formatted as a pressure–temperature (P–T) matrix, maintaining dimensional consistency and interpolation continuity within the Simscape environment. The use of verified Reference Fluid Thermodynamic and Transport Properties (REFPROP) data ensured the thermodynamic accuracy of methane behavior near the saturation curve, providing a reliable foundation for the two-phase flow simulation, as summarized in TABLE I.

TABLE I
METHANE PROPERTIES DEFINITION

	Methane: Specified state points									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Temperature(°C)	-161,64	-152,53	-146,44	-141,71	-137,80	-161,64	-152,53	-146,44	-141,71	-137,80
Pressure(bar)	1,00	2,00	3,00	4,00	5,00	1,00	2,00	3,00	4,00	5,00
Density(kg/m³)	422,59	408,95	399,38	391,66	385,04	1,7946	3,3966	4,9486	6,4792	8,0016
Internal Energy(kJ/kg)	-0,794	31,137	52,847	69,909	84,241	454,84	466,06	472,85	477,66	481,31
Entropy(kJ/kg.K)	-0,0050	0,27035	0,44604	0,57838	0,68597	4,5787	4,3601	4,2331	4,1426	4,0716
Phase	Liquid	Liquid	Liquid	Liquid	Liquid	Gas	Gas	Gas	Gas	Gas
Thermal Conductivity(W/m.K)	0,18393	0,17107	0,16238	0,15564	0,15005	0,011393	0,012711	0,013677	0,014483	0,015195
Kinematic Viscosity(cSt)	0,27723	0,23836	0,21678	0,20198	0,19081	2,4063	1,3684	0,98476	0,77973	0,65038
Prandtl	2,2166	2,0257	1,9291	1,8688	1,8281	0,84012	0,84084	0,84563	0,85240	0,86055

Cavitation inception was mathematically defined as the condition where the local static pressure of the liquid becomes lower than the saturation vapor pressure corresponding to the local temperature, as expressed by the cavitation inception condition given in Equation (1) [1], [2]:

$$p_{local} \leq p_{vapor}(T) \quad (1)$$

The saturation vapor pressure, $p_{vapor}(T)$ can be approximated by the Clausius–Clapeyron relation given in Equation (2) [6]:

$$p_{vapor}(T) = p_{sat} exp[-\frac{L_v}{\mathrm{R}}(\frac{1}{\mathrm{T}} - \frac{1}{T_{ref}})] \quad (2)$$

The presented equations are consistent with the pressure–temperature (P–T) dependent two-phase thermodynamic approach adopted in this study, where cavitation inception is characterized by the equilibrium between local static pressure and saturation vapor pressure. This formulation ensures thermodynamic consistency between the mathematical representation and the two-phase modeling framework implemented in Simscape.

TABLE II
DEFINITION OF SYMBOLS USED IN THE CAVITATION INCEPTION CONDITION AND CLAUSIUS–CLAPEYRON RELATION EQUATIONS

	Definition of Symbols Used in the Equations	
	Description	**Unit**
p_{local}	Local static pressure of the fluid	Pa
$p_{vapor}(T)$	Saturation vapor pressure corresponding to local temperature	Pa
p_{sat}	Reference saturation pressure at temperature T_{ref}	Pa
L_v	Latent heat of vaporization	kJ/kg
R	Specific gas constant of the fluid	J/(kg·K)

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T	Absolute temperature	K
T_{ref}	Reference temperature	K

This thermodynamic relationship represents the phase transition boundary between liquid and vapor states, providing the theoretical foundation for the two-phase modeling approach adopted in this study. The symbols and parameters used in Equation (1) and Equation (2) are defined in TABLE II.

C. System Components and Configuration

The developed Simscape model represents the cryogenic centrifugal pump system as an integrated two-phase fluid and mechanical rotational domain, capturing the dynamic behavior of liquid methane under varying inlet pressure and temperature conditions. The system consists of an Inlet Reservoir (2P) that defines the suction boundary and provides the initial fluid inventory, followed by a Suction Pipe (2P) that models pressure loss and possible vapor formation along the inlet line. The Centrifugal Pump (2P) block represents the impeller region, where mechanical energy supplied by an Ideal Angular Velocity Source (operating at approximately 6500 rpm) is converted into hydraulic head. Downstream of the pump, a Discharge Pipe (2P) and a Constant Volume Chamber (2P) simulate the outlet flow path and pressure stabilization, respectively, before the working fluid returns to the Outlet Reservoir (2P).

To monitor the dynamic behavior of the system, measurement components were placed at both the suction and discharge sides. Pressure, Temperature & Internal Energy Sensors (2P) were implemented to capture the thermodynamic state of the fluid, while Flow Rate Sensors (2P) and Vapor Quality Sensors (2P) were used to measure mass flow rate and vapor fraction, respectively. The sensor outputs were converted into Simulink signals using PS–Simulink Converter blocks and visualized through separate scopes for the inlet and outlet domains.

The overall flow direction progresses from the Inlet Reservoir to the Outlet Reservoir, passing sequentially through the suction, impeller, and discharge sections. The inlet pressure and temperature act as upstream boundary conditions, while the outlet chamber establishes a quasi-stable pressure reference, allowing both steady and cavitating conditions to be simulated. This configuration provides a realistic representation of transient two-phase flow behavior in cryogenic pump operations.

D. Boundary Conditions and Scenarios

The boundary conditions for the simulation were defined using *Reservoir (2P)* blocks positioned at both the inlet and outlet of the system. These reservoirs established the thermodynamic state of the working fluid—liquid methane—by specifying the pressure and energy characteristics of the system boundaries. A set of simulations was conducted under different reservoir pressure levels ranging from 4 to 4.5 bar, with a port cross-sectional area of 0.01 m^2 applied uniformly at both ends of the model to maintain symmetrical operating conditions.

Two distinct simulation scenarios were configured to evaluate the pump behavior under different thermodynamic regimes. In the normal operating condition, the reservoir energy specification was set to Degree of Subcooling, with a subcooling value of 10 °C. This configuration ensured that the working fluid remained in the subcooled liquid phase, representing stable, non-cavitating flow conditions. Conversely, the cavitating condition was simulated by changing the reservoir energy specification to Vapor Quality, with a set value of 0.1, corresponding to a two-phase mixture at the pump inlet and outlet. This condition facilitated the analysis of vapor bubble formation and its influence on the pressure and flow stability across the system.

By comparing the system responses under these two boundary conditions, the simulation effectively captured the transition from subcooled liquid flow to cavitating two-phase flow, allowing a detailed assessment of the dynamic effects of cavitation on cryogenic pump performance.

III. RESULTS

Two simulation cases were conducted to evaluate the dynamic behavior of the cryogenic centrifugal pump under both normal and cavitating conditions. The analysis focused on the variations of pressure, temperature, flow rate, and vapor quality at the pump inlet and outlet, as obtained from the implemented sensor network.

Under normal operating conditions, the sensor outputs indicated stable inlet and outlet pressures, constant flow rate, and nearly uniform temperature values, as illustrated in Figure 2 and Figure 3. These results confirm that the working fluid remained in the subcooled liquid region, with no observable vapor formation or hydrodynamic instability throughout the operation. The absence of oscillations in pressure and flow rate signals demonstrates steady-state performance, validating the thermodynamic consistency of the model in single-phase flow conditions.

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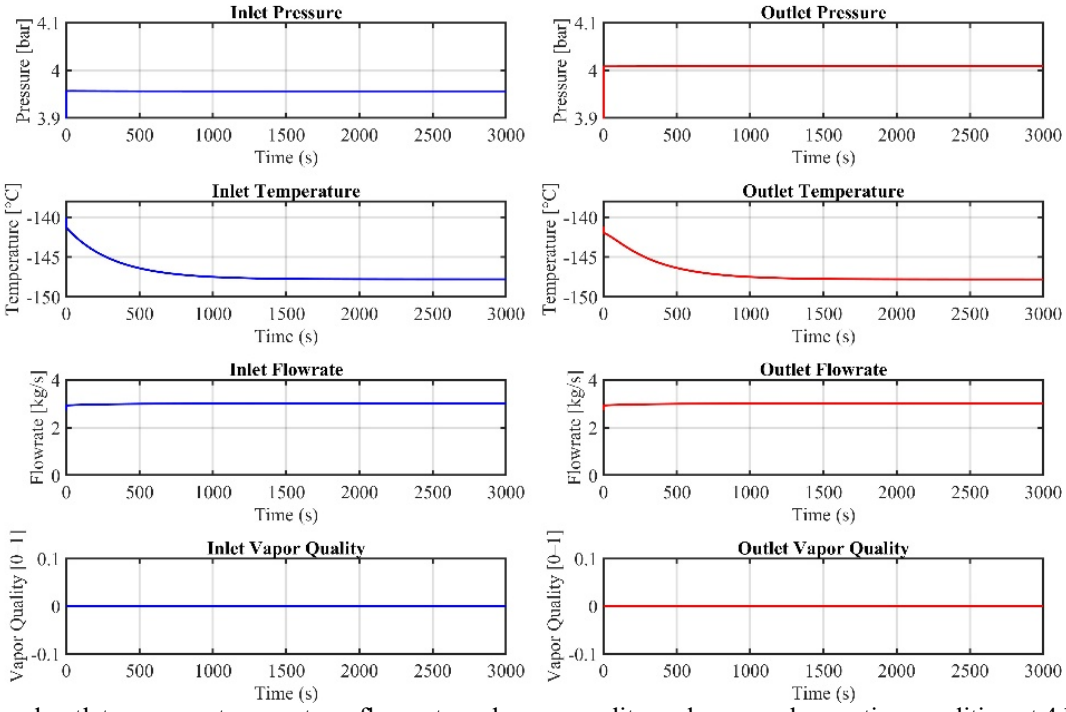

Fig. 2 Inlet and outlet pressure, temperature, flow rate and vapor quality under normal operating condition at 4 bar

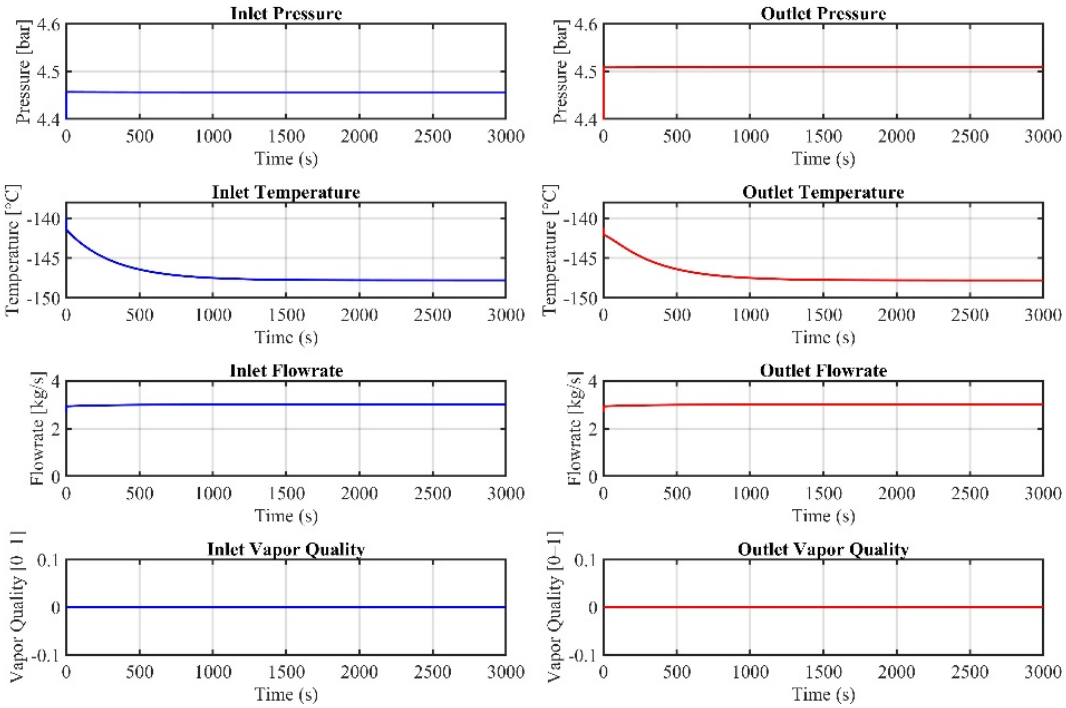

Fig. 3 Inlet and outlet pressure, temperature, flow rate and vapor quality under normal operating condition at 4.5 bar

In contrast, under cavitating conditions, the model exhibited clear fluctuations in both inlet and outlet pressures, as well as a noticeable decrease in flow rate accompanied by an increase in vapor quality, as shown in Figure 4 and Figure 5. These transient variations reflect the onset of vapor bubble nucleation and the subsequent development of a two-phase flow regime within the impeller and suction regions. The observed periodic pressure drops correspond to the collapse and reformation of vapor cavities, indicating a loss of flow stability and reduced hydraulic efficiency. Additionally, the slight temperature fluctuations confirm localized vaporization and condensation effects associated

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with cavitation dynamics in cryogenic fluids. The transient pressure drops observed during cavitation are attributed to the rapid collapse of vapor cavities within the impeller, resulting in localized head loss and unsteady flow behavior.

Under cavitating conditions, a distinct transient behavior is observed in the temperature profile, characterized by an initial rise followed by a gradual decrease until reaching steady-state equilibrium. The short-term temperature increase corresponds to the compression and local energy accumulation occurring at the pump inlet as the pressure approaches the saturation limit. Once the local static pressure falls below the saturation vapor pressure, rapid vaporization initiates, and the latent heat of vaporization is absorbed from the surrounding liquid phase, leading to a noticeable temperature drop. After this transient phase, the heat and mass transfer between the liquid and vapor phases stabilize, resulting in a nearly constant temperature profile. This behavior confirms the strong coupling between pressure and temperature dynamics under cryogenic cavitation conditions, where thermodynamic effects dominate the transient response of the fluid.

Overall, the comparative results between the two cases demonstrate the model's capability to accurately capture the thermodynamic transition from subcooled liquid to two-phase flow, as well as the associated pressure oscillations, flow instabilities, and vapor generation mechanisms. These findings verify the reliability of the developed Simscape model in reproducing cavitation behavior in cryogenic centrifugal pumps, providing a valuable foundation for future design and control optimization studies.

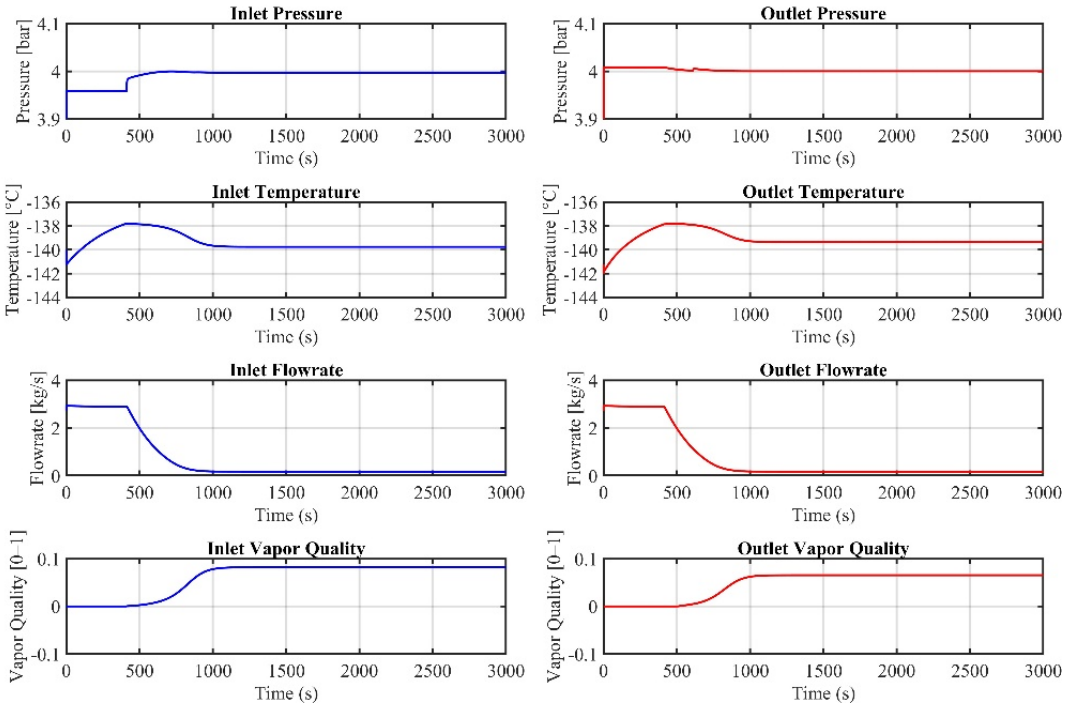

Fig. 4 Inlet and outlet pressure, temperature, flow rate and vapor quality under cavitating condition at 4 bar

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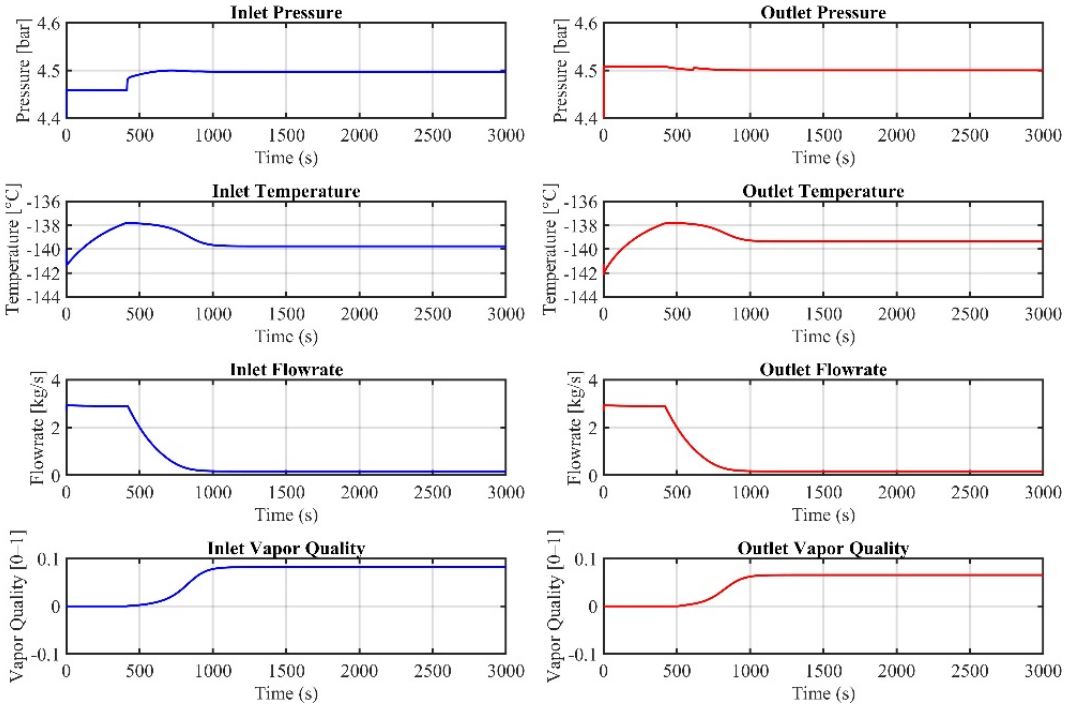

Fig. 5 Inlet and outlet pressure, temperature, flow rate and vapor quality under cavitating condition at 4.5 bar

IV. CONCLUSIONS

This study successfully developed and demonstrated a dynamic simulation model for analyzing cavitation behavior in a cryogenic centrifugal pump operating with liquid methane. The Simulink/Simscape-based framework accurately represented the thermophysical properties of methane through tabulated data derived from NIST REFPROP and effectively captured the thermodynamic transition between subcooled and two-phase flow regimes. The results revealed that under cavitating conditions, pressure and flow rate fluctuations became more pronounced due to vapor bubble formation, confirming the model's capability to replicate cavitation-induced instabilities. Sensor-based monitoring of pressure, temperature, and vapor quality provided detailed insight into the onset and propagation of cavitation within the pump system.

Overall, the findings emphasize that cavitation in cryogenic pumps is not merely a thermodynamic process but a dynamic instability that significantly affects hydraulic performance and operational stability. The proposed modeling approach offers valuable insights for the development of advanced cavitation prevention and early detection strategies in cryogenic pump systems and provides a solid foundation for future studies aimed at optimizing cryogenic pump process design, improving control algorithms, and mitigating cavitation-related performance losses.

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