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Immersion Cooling in Data Centers: A Comprehensive Review of Benefits, Challenges, and Future Directions

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ABSTRACT

Immersion cooling has emerged as a promising solution for the escalating thermal management challenges in the contemporary and modern (next generation) data centers, where traditional air-cooling systems are increasingly inadequate due to rising power densities in microprocessors. The evolution of immersion cooling technologies, highlighting their benefits and the challenges associated with their implementation, is explored in this review. Two-phase microchannel cooling has often been cited as a highly efficient alternative, which can help achieve significant energy savings over air cooling. Subsequent studies have expanded on methods like refrigerant touch cooling, thermosiphon systems, and geothermal immersion cooling. All these strategies can help achieve enhanced energy efficiency, reduced operational costs, and improved Power Usage Effectiveness (PUE). Immersion cooling has been demonstrated to support denser CPU packaging and meet the demands of high-performance computing environments. Despite these advantages, challenges persist, including the need for specialized infrastructure, potential risks related to liquid handling, and integration with existing systems. Advances in environmentally friendly cooling fluids and optimized airflow management have begun to mitigate some of these issues. To fully realize the potential of immersion cooling, future research endeavors should focus on developing standardized protocols and best practices to facilitate its widespread adoption. Enhancing the compatibility of cooling fluids with a broader range of hardware components will be crucial, as will designing systems that are easier to integrate with existing data center infrastructure. Exploring hybrid cooling solutions that combine immersion cooling with other efficient methods could offer additional benefits. Further investigation into the long-term reliability, maintenance requirements, and environmental impacts of immersion-cooled systems is essential. Integrating immersion cooling with renewable energy sources and waste heat recovery systems could also enhance sustainability and operational efficiency (e.g., for thermal desalination and wood drying applications). The literature reports can be utilized to identify a clear trend toward adopting immersion cooling as a key strategy for improving energy efficiency and thermal management in data centers. Hence, ongoing research and development efforts need to be redirected to overcoming these remaining obstacles, thus paving the way for more energy efficient data center operations with reduced footprint for water and power consumption in the future; while also improving the sustainability, reliability, robustness, and resilience of these platforms.

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KEY WORDS: Two phase cooling, Thermal management, Data center, Dielectric fluid, Power density

NOMENCLATURE

A_f	area enhancement factor	(-)	Re	Reynolds number	(-)
C_p	specific heat capacity and constant pressure	(J/kg-K)	Re_v	vibrational Reynolds number	(-)
F	bubble departure frequency	(Hz)	T_s	surface temperature	(°C)
f_i	interfacial friction factor	(-)	T_1	saturation temperature	(°C)
g	gravitational acceleration	(m/s^2)	T_{sub}	sub cool temperature	(°C)
h_{fg}	latent heat of vaporization	(J/kg)	δ	vapor layer thickness	(m)
L	length	(m)	λ	wavelength	(m)
Nu	Nusselt number	(-)	ν	kinematic viscosity	(m^2/s)
P	pressure	(Pa)	ρ_f	density of fluid state	(kg/m^3)
P_c	critical pressure	(Pa)	ρ_g	density of gaseous state	(kg/m^3)
R	radius of bubble	(m)	σ	surface tension	(N/m)
R_i	individual gas constant	(m)			

1. INTRODUCTION

Since the invention of electronics, integrated circuits have grown by leaps and bounds following the trend predicted by Moore's Law that with every passing year, the number of transistors in a circuit has been twice [1]. The integrated circuit is a sandwich consisting of millions of transistors embedded in a silicon wafer made up of semiconductors. Electronics have transformed our lives from computing to mobile devices. These applications have boosted the growth of integrated circuits from four transistors in the first integrated chip [2] to more than 200 billion transistors embedded in a chip [3]. With the increasing number of transistors in the chip and rapid expansion of the scale of data centers, the power density has also increased. The data centers consume 1% of total energy consumption in the entire world [4]. In the United States, the energy consumption of data centers stood up to 2% of net consumption [5].

With this enormous consumption, thermal management also poses a threat to restricting expansion due to its limitations in cooling down the power usage at the data centers [6]. The cooling and electrical systems consume most of the energy. Around 52% of electricity consumed in a data center is by IT equipment, 38% by cooling systems, and 10% by other equipment [7, 8]. A study showed that the electronics industry is facing a challenge in dealing with high heat flux coming out of the chip which is raising the temperature of the chip to alarming levels. The major cause of failure of electronic chips is thermal failure, which stands at 55% followed by vibration which accounts for only 20%, and humidity and dust accounting for 19% and 6% respectively [9, 10]. Therefore, the integrated circuit industry needs efficient thermal management technologies, which are expected to keep improving the performance and reliability of electronic devices [11].

Current industrial practices in data center cooling are evolving rapidly as the demand for energy efficient thermal management solutions increases. Traditionally, air conditioning and raised floor cooling systems have been the primary methods used to manage the heat generated by servers [12]. However, these conventional methods are becoming less effective and more costly as data centers grow in scale and computing densities increase [13]. As a result, many industries are now adopting more advanced techniques, such as direct-to-chip liquid cooling [14], hybrid air-liquid cooling systems [15], and immersion cooling [16]. Immersion cooling is gaining traction due to its ability to directly absorb and remove heat, resulting in significant reductions in both energy consumption and operating costs [17]. Additionally, major technology companies and data centers are exploring two-phase immersion cooling for its superior heat transfer capabilities, which makes it highly efficient for managing increasingly dense and powerful server architectures. The growing interest in immersion cooling signifies a shift in industrial practices toward greener, more efficient, and reliable solutions, as industries strive to address the limitations of conventional air-cooling methods.

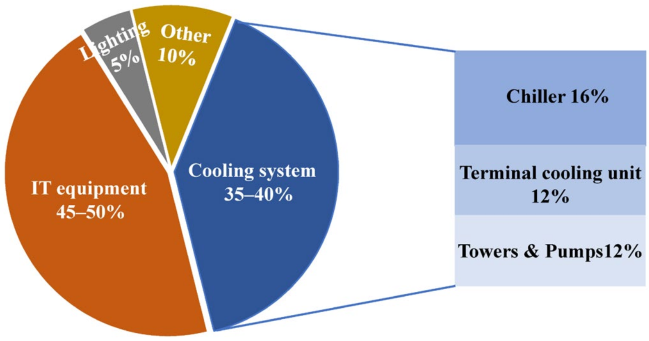

Fig. 1 Energy consumption segments of a typical data center [18].

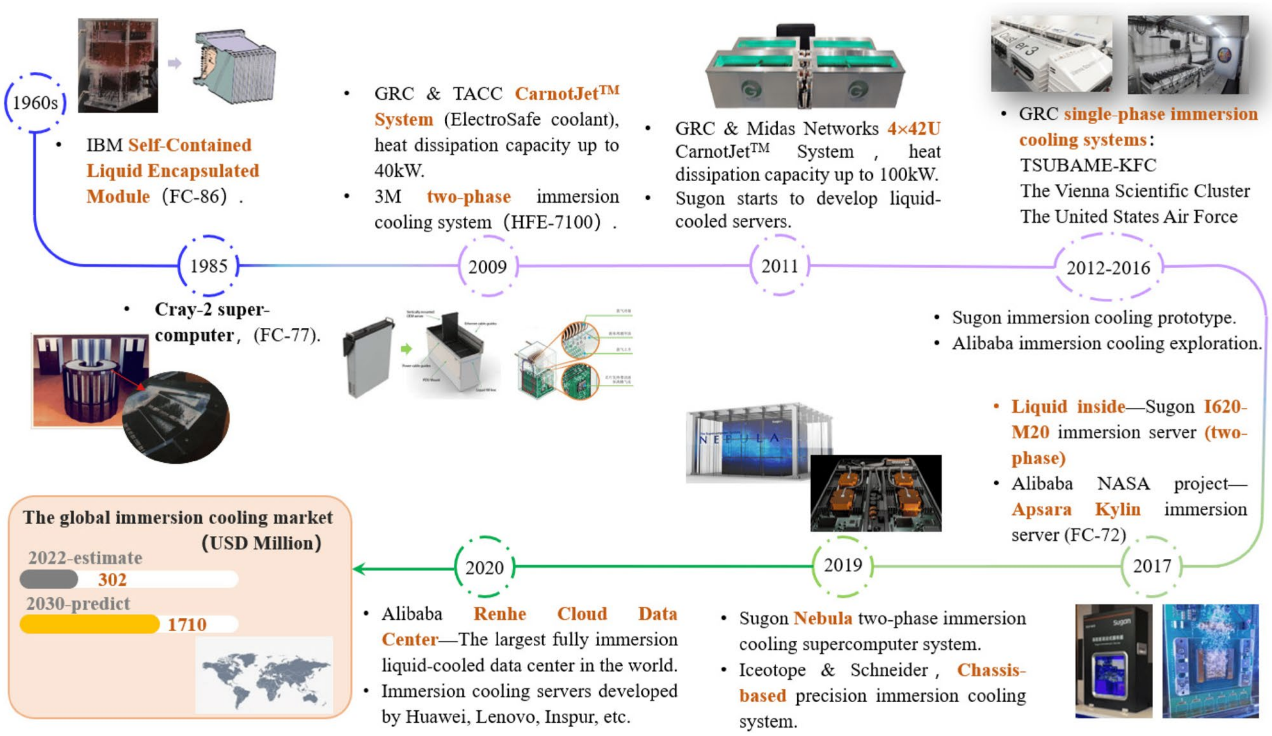

Fig 2 Timeline of key developments and innovations in the field of immersion cooling [19].

2. LITERATURE REVIEW

Contemporary technology platforms for various cooling configurations (and thermal management) focused on data centers and electronic components applications - range from traditional cold plate systems to advanced immersion cooling techniques. Each of these configurations leverage distinct mechanisms for augmenting rates of heat dissipation (with ever decreasing form factors) as shown in

Fig ***3***. Cold plate cooling involves placing a cold plate directly on the motherboard, using a circulating fluid to absorb heat, sometimes incorporating a phase change for greater efficiency [20]. The thermal management platforms leveraging phase change heat transfer options allows the coolant to evaporate and condense, leveraging the latent heat of vaporization with the aim of achieving superior rates of heat removal. Immersion cooling methods, on the other hand, submerge the entire motherboard in a coolant (e.g., typically a dielectric fluid). In single-phase immersion cooling, heat is directly absorbed by the fluid (i.e., by leveraging sensible heat storage), which can be circulated via a pump or convection to an external heat exchanger for further cooling and rejection of the thermal load to the ambient [21]. Two-phase immersion cooling takes this a step further in terms of complexity, where the dielectric fluid boils upon contact with the heated components, and the vapor generated is condensed back into liquid form (in another segment of the thermal management platform – which is typically away from the source of heat). This phase change heat transfer transport mechanism leverages latent heat for thermal storage and therefore provides a high heat transfer coefficient, making it highly effective for handling large thermal loads (especially in small form factors). The transition from cold plate cooling to two-phase immersion represents ongoing advancements to address the increasing heat densities of modern high-performance systems. However, the price for this innovation (in terms of augmented performance and better sustainability) is the added risks associated with multi-phase flows (e.g., flow instabilities associated with two-phase flows), which can lead to degradation in the operational reliability of such platforms (e.g., compared to that of single-phase flow systems). This can also lead to degradation in robustness, resilience and dependability of these systems, especially when forced to operate in sub-optimal conditions (e.g., when associated with “black swan” type catastrophic operating conditions).

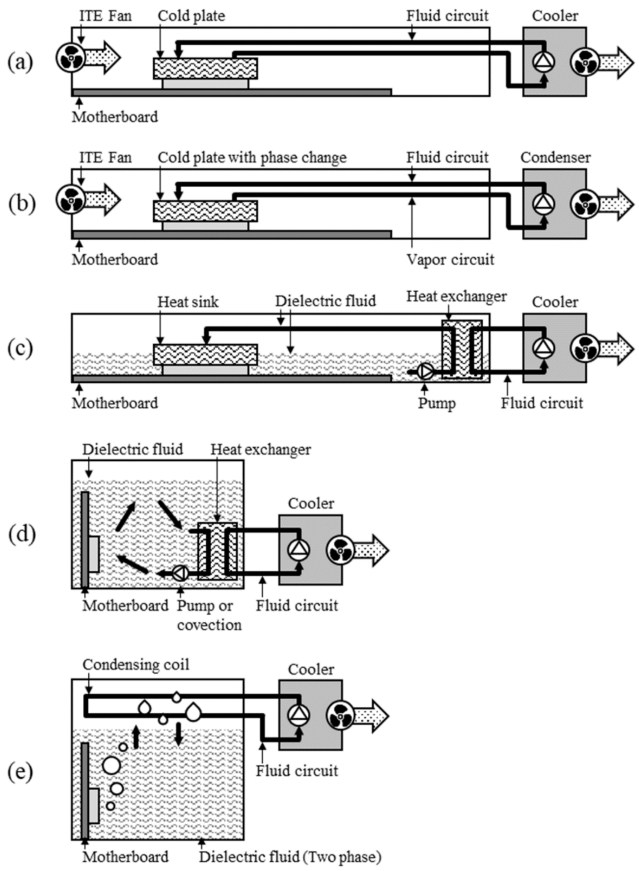

Fig 3 Five different cooling configurations commonly used for data centers [22]

2.1 Immersion Cooling

In 1899, the first patent was registered by Richard Fleming of Lynn using mineral oil as a coolant to cool down transformers [23]. In the realm of electronics, Oktay Sevgin of IBM was the first to study the feasibility of liquid dielectrics to cool computers at IBM [24] and in 1968, Richard C. Chu and John H. Seely, working for IBM, patented an "immersion cooling system for modularly packaged components" [25]. This marked an early recognition of the potential for cooling microelectronic components with liquids. Subsequently, Seymour R. Cray Jr., the founder of Cray Research, LLC, patented an "Immersion-cooled high-density electronic assembly" [26]. The concept gained further traction in the mid-1980s when companies like IBM, Univac, Control Data, and Hitachi introduced indirectly water-cooled mainframe computers [27]. In 1995, the Cray T90 was released, utilizing a liquid-to-liquid heat exchanger and one- or two-phase immersion coolant for heat removal [28]. In the 21st century, there has been a noticeable surge in interest and innovation in immersion cooling systems. This trend is evident from various key developments. In 2006, Hardcore Computer Inc. was founded, introducing a closed-chassis-style PC for gaming based on the immersion cooling concept [29]. These milestones underscore the growing interest and investment in immersion cooling technologies over the past two decades. Immersion cooling can be categorized into single-phase and two-phase systems. The heat transfer coefficient in single-phase immersion cooling is already quite high due to effective convective heat transfer between the coolant and the heated components. However, in two-phase immersion cooling, the heat transfer coefficient is significantly higher, as shown in

Fig ***4***, due to the additional energy absorbed during the phase change from liquid to vapor, making it exceptionally efficient for high-power density applications.

In two phase immersion cooling, the system operates based on the principles of the boiling curve

Fig ***5***, particularly utilizing nucleate boiling up to the point of critical heat flux (CHF). In nucleate boiling, the coolant absorbs heat from the electronic components and forms vapor bubbles at the surface, which are then released into the liquid [30]. This phase change is highly effective in transferring large amounts of thermal energy, maintaining optimal component temperatures [31].

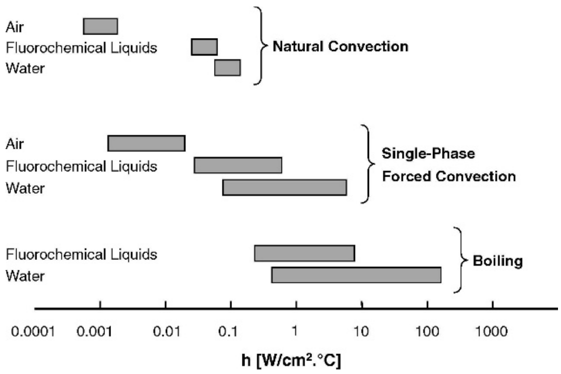

Fig 4 Heat Transfer Coefficients for Various Cooling Methods [32]

Immersion cooling systems are designed to operate within the nucleate boiling regime to maximize heat dissipation while avoiding the transition beyond CHF, which would reduce cooling efficiency and potentially damage electronic components. In this regime, a significant amount of heat flux can be dissipated with a relatively low difference between the wall temperature and the saturation temperature, known as wall superheat. In film boiling, the heated surface is entirely covered by a continuous vapor layer as shown in

Fig ***6***. Given that film boiling is less efficient compared to nucleate boiling, it is preferable to avoid it in practical applications whenever possible [33].

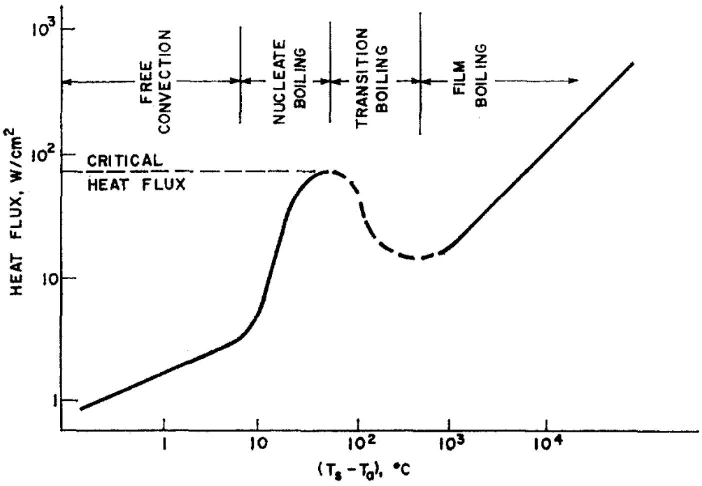

Fig 5 Boiling curve [34]

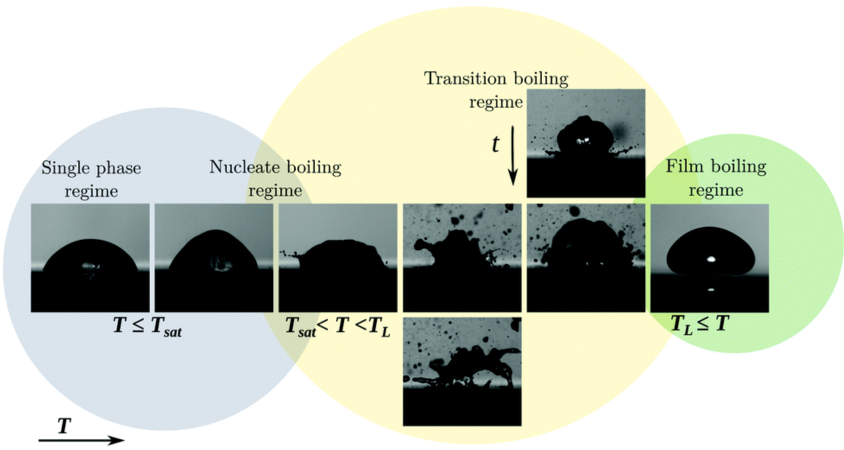

Fig 6 Bubbles growth under the microscope [35]

In two-phase immersion cooling, the dielectric fluid evaporates upon contact with heated components, taking advantage of the latent heat of vaporization. This phase change results in more efficient heat transfer, particularly in systems with high thermal loads, such as data centers and high-performance computing [36]. Two-phase immersion cooling technology was found to offer minimal thermal resistance, with values as low as 0.247 °C/W, creating a highly efficient heat transfer path. This results in superior computational performance and greater efficiency when compared to traditional air-cooling methods [37]. Kulkarni et al. present a hybrid liquid cooling system that integrates cold plates and immersion fluid to cool high thermal design power (TDP) components, providing a highly efficient solution for data centers with energy reclamation capabilities [38]. In data centers, Baris Burak Kanbur and colleagues compared single-phase and two-phase immersion cooling systems, finding that the two-phase systems exhibited a significantly better coefficient of performance, reducing energy consumption by up to 79% compared to single-phase systems [39]. Wang et al. applied two-phase immersion cooling to a high-repetition avalanche transistor pulse generator, successfully reducing thermal resistance and significantly improving the system's performance at high frequencies[40]. Enright et al. describe a two-phase immersion cooling platform that uses dielectric fluid vaporization to manage the temperature of heat-generating computer components, emphasizing its efficiency in high-performance computing [41].

Coolants play a vital role in immersion cooling as they are the primary medium that comes into direct contact with the electronic components [42]. These fluids must be safe to use, posing no significant hazards in the event of a leak, while also being dielectric to prevent electrical conductivity [43]. The choice of coolant is crucial for ensuring effective heat transfer, protecting the components, and maintaining system reliability [44]. These requirements make the selection of an appropriate coolant a critical aspect of designing an efficient and safe immersion cooling system. For instance, Yang Li et al. explored two-phase immersion cooling using fluorinated liquids like SF33 to cool lithium-ion batteries, demonstrating its ability to maintain lower and more consistent temperatures compared to forced air cooling under high discharge conditions [45]. Xiang-Wei Lin's study also compared different battery thermal management systems, highlighting that two-phase immersion cooling offered superior performance in suppressing temperature rise and maintaining temperature uniformity at high discharge rates. The use of a coolant like R1336mzz(Z), with a high boiling heat transfer coefficient, was found to be particularly effective for thermal management under demanding conditions [46]. Sun et al. found that using Novec 7000, with a lower boiling point than Novec 649, reduced chip temperatures significantly in two-phase immersion cooling systems for data centers [47]. Niazmand et al. utilized FC-72 in simulations, showing its effectiveness in reducing overheating and thermal shadowing in multi-chip modules during two-phase immersion cooling [48]. Ramakrishnan et al. investigated a two-phase cooling cold plate system using dielectric fluids in high-density servers, finding that it could dissipate heat flux levels up to 63.6 W/cm², maintaining base temperatures below 75°C [49]. Liu et al. demonstrated that mineral oil immersion cooling effectively maintains lithium-ion battery temperatures below 40°C at high discharge rates, with improved temperature uniformity and safety [50]. Trimbake et al. experimentally validated the effectiveness of mineral oil as a cooling medium for lithium-ion batteries, maintaining uniform skin temperature and reducing peak temperatures during high-rate charge-discharge cycles [51].

Finally, the immersion cooling literature is reviewed and its important potential for thermal management in high performance computing systems and energy storage solutions is established. The use of dielectric fluids has been particularly effective in improving temperature regulation, system efficiency, and operational safety. With an increasing demand for more efficient cooling technologies, continued investigation into identifying appropriate fluid properties and system configurations is needed to enable the widespread use of immersion cooling.

3. IMMERSION COOLING

To deal with high heat flux, immersion cooling provides an alternative way by allowing the contact of high-heat capacitance fluids to come directly in contact with the electronic devices absorbing enormous amounts of thermal energy and acting as a heat sink [52]. A conventional data center consumes one-third of the energy to cool it down through air cooling [53]. However, water absorbs thirty times more heat than air [54].

3.1 Prediction Models

The boiling process of an electronic fluorinated liquid on a component's surface, resulting in bubble formation, requires nucleation sites along with a specific level of superheat. By analyzing the balance of internal and external forces acting on the bubble, and applying the Clausius-Clapeyron equation, the temperature on the surface of the chip can be expressed as

$$T_s - T_1 = \frac{2\sigma T_1}{h_{fg}R}\left(\frac{1}{\rho_g} - \frac{1}{\rho_f}\right) \tag{1}$$

where, T_s is the surface temperature of the chip, T_1 is the saturation temperature of the fluid. σ is the surface tension of the fluid. h_{fg} is the latent heat of vaporization. R is the radius of the bubble at nucleation and ρ_g and ρ_f are densities of gaseous and fluid states respectively.

Critical Heat Flux (CHF) is a fundamental aspect of immersion cooling, representing the maximum heat flux that a cooling system can manage before a drastic reduction in heat transfer occurs due to vapor film formation. This phenomenon, known as the "boiling crisis," creates an insulating vapor layer between the heated surface and the cooling liquid, leading to potential overheating of critical components [55]. Ghaffari et al. conducted pool boiling experiments on bare copper surfaces immersed in Novec 649™ and Novec 7000™ dielectric liquids to determine the CHF associated with each fluid, providing valuable insights into the heat transfer limits for these cooling agents [56]. Research into surface enhancements, such as optimized groove sizes and "breathing phenomena," has demonstrated significant improvements in CHF for immersion cooling applications using water and FC-72 [57]. The

Table ***1*** below discusses various correlations proposed by different authors to determine the CHF, offering models that account for factors such as bubble dynamics, hydrodynamic instability, macrolayer dryout, and hotspot formation, each contributing to a deeper understanding of CHF under immersion cooling conditions.

The Nusselt number is important because it helps quantify the efficiency of heat transfer in boiling processes. Rohsenow developed an initial correlation for predicting nucleate pool boiling heat transfer based on experimental data [58]. The updated correlation incorporates vibrational Reynolds number and area enhancement factor to account for the effects of vibration and surface modifications, thereby improving its applicability to different scenarios [59].

$$Nu = 0.18783\ Re^{0.3687} Pr^{1.929} {Re_v}^{0.033} {A_f}^{9.5489} \tag{2}$$

where Re_v is vibrational Reynolds number and A_f is area enhancement factor. In terms of the local maximum Nusselt number, an enhancement of approximately eightfold is observed compared to natural convection without a bubble, when the bubble follows a zigzag path and is close enough to impact the wall [60].

3.2 Construction:

Recent advancements in the construction of two-phase immersion cooling systems have focused heavily on enhancing efficiency, mitigating fluid losses, and improving control over the cooling process through innovative designs and components. Several patents introduce specialized systems for managing vapor generation and condensation, which are critical for effective two-phase cooling. International Business Machines Corporation introduced the concept of a hybrid immersion cooled server with integral spot and bath cooling using two different coolants, primary and secondary coolants [61]. Bitfury describes an active vapor management system that uses a combination of a primary condenser and auxiliary condensers. This system efficiently captures vapor and returns it to the immersion tank, thereby reducing fluid losses. Such an approach is essential to maintain cooling performance, especially during fluctuating power loads [62].

Table 1 Summary of CHF correlations proposed by various authors for different predictive models[63]

Authors	Model	Correlations	References
Rohsenow and Griffith	Bubble interaction model	$q_{CHF} = 0.012\rho_g h_{fg}\left(\frac{\rho_f - \rho_g}{\rho_g}\right)^{0.6}$	[64]
Zuber and Tribus	Model of hydrodynamic instability	$q_{CHF} = 0.131.L\rho_v\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v}\right)^{\frac{1}{4}}$	[65]
Haramura and Katto	Macrolayer evaporation model	$q_{CHF} = \rho_f h_{fg}\delta\left[1 - 0.0584\left(\frac{\rho_g}{\rho_f}\right)^{1/5}\right]f$	[66, 67]
Yagov	Hot/dry spot model	$q_{CHF,h} = 0.5\frac{h_{fg}^{81/55}\sigma^{9/11}\rho_g^{13/110}\lambda^{7/110}g^{21/55}f(Pr)}{\nu^{1/2}C_p^{3/10}R_i^{79/110}T_s^{21/22}}, \frac{P}{P_c} < 0.001$ $q_{CHF.l} = 0.06h_{fg}\rho_g^{3/5}\sigma^{2/5}\left[\frac{g(\rho_f - \rho_g)}{\mu_f}\right]^{1/5}, \frac{P}{P_c} > 0.03$ $q_{CHF} = (q_{CHF.h}^3 + q_{CHF.l}^3)^{1/3}, 0.001 \le \frac{P}{P_c} \le 0.03$ For nonmetallic liquids $f(Pr) = \left(\frac{Pr^{9/8}}{1 + 2Pr^{1/4} + 0.6Pr^{4/24}}\right)^{4/11}$ For metallic liquids $f(Pr) = 0.5$	[68, 69]
Galloway and Mudawar	Interface lift-off model	$q_{CHF} = 2^{-113/24}3^{5/6}\left(\frac{\pi}{f_i}\right)^{1/4}\left(\frac{\rho_f}{\rho_f + \rho_f}\right)\rho_g h_{fg}\left(1 + \frac{C_{p,f}\Delta T_{sub}}{h_{fg}}\right)\left[\frac{\sigma g(\rho_f - \rho_g)}{\rho_g^2}\right]^{1/4}$	[70, 71]

Another key construction innovation involves scalable heat management, as described by Microsoft. This patent incorporates thermal blocks that serve as additional heat sinks within the immersion tank. The blocks provide extra thermal mass to help balance cooling demand during peak power consumption periods, thus maintaining the server components at safe temperatures even when power fluctuations occur. This feature is significant for the design of robust two-phase cooling systems that must maintain high reliability in dynamic operational environments [72].

Recently, Microsoft invented self-contained immersion cooling server assemblies where the server is at least partially immersed in coolant. They claim a method for maintaining servers in immersion cooling enclosures, involving purging coolant upon power removal, allowing enclosure access, and subsequent refilling. Additionally, they propose variations including purging with nitrogen, automatic enclosure opening, and performing physical operations on the server [73]. Intel Corporation reported about the construction of immersion systems by proposing a design that allows the modulation of the ambient space volume within the cooling environment. This adjustable volume provides more precise control over the temperature stability of the dielectric fluid under varying workloads. The system's output is also designed to channel heated fluid for secondary purposes, such as building heating, effectively integrating the cooling system into broader energy efficiency strategies [74].

Further improvements in the construction of two-phase immersion systems include adaptive mechanisms for coolant properties. Intel introduces a system that allows for the dynamic modulation of the boiling point of the coolant, adapting the fluid characteristics based on environmental conditions. This dynamic adjustment ensures optimal cooling performance regardless of external temperature fluctuations [75]. Another patent features a multi-stage cooling system, which includes multiple immersion cooling stages that activate based on thermal load. This staged approach enables better efficiency and power management by reducing unnecessary cooling during low thermal loads [76]. Moreover, hybrid immersion cooling systems, such as the one described by Microsoft, leverage both single-phase and two-phase cooling designs to maximize flexibility and efficiency in data center applications [77]. These patents collectively highlight ongoing efforts to refine the construction of two-phase immersion cooling systems by improving core elements such as vapor management, heat sink integration, and modular adaptability. The focus on both functional efficiency and maintainability reflects the increasing importance of designing versatile, scalable, and reliable cooling solutions for modern high-performance computing and data center environments. These developments aim to enhance system resilience, reduce operational costs, and facilitate broader integration into existing infrastructure, paving the way for more widespread adoption of two-phase immersion cooling technology.

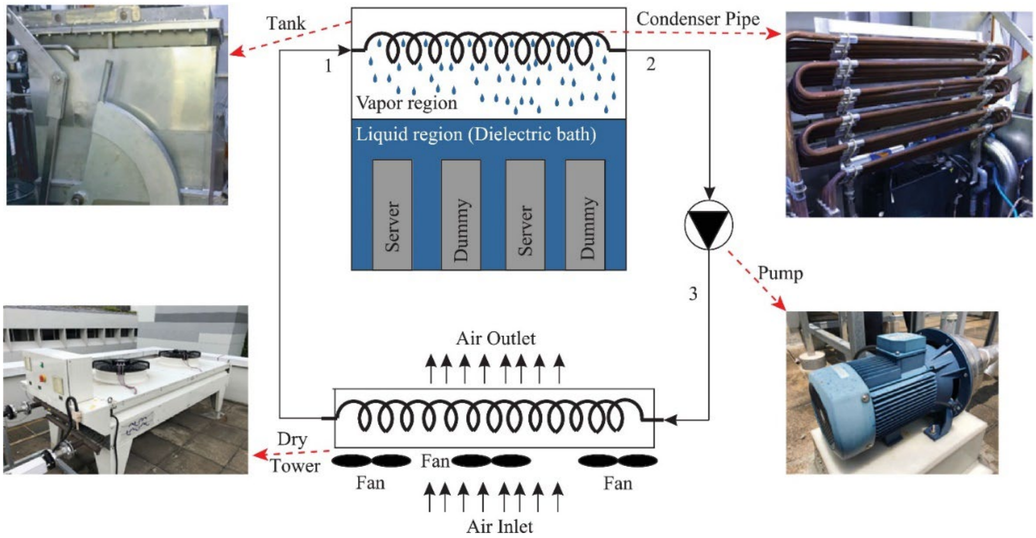

Fig 7 Operational setup of a two-phase immersion cooling system [78]

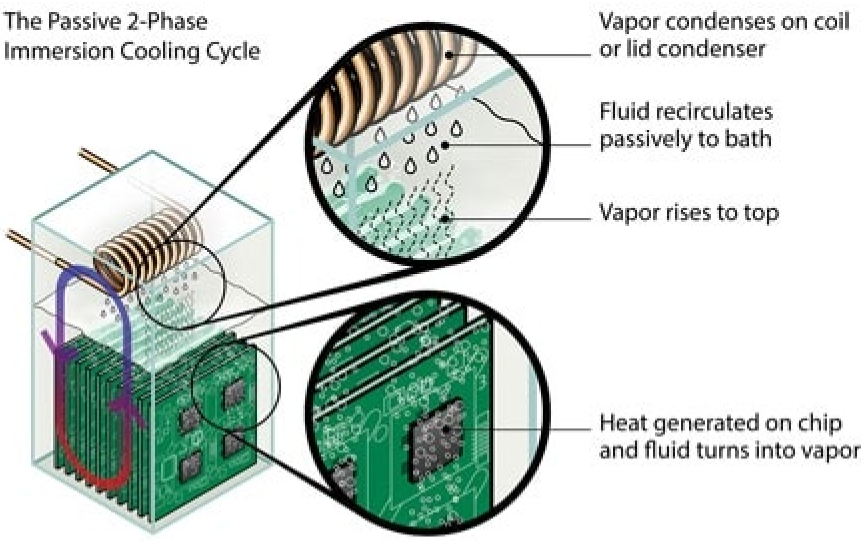

Fig 8 Schematic of two-phase immersion cooling [79]

4. RECENT WORK

The recent studies in two-phase immersion cooling highlight an increased focus on utilizing innovative materials, cooling fluids, and system designs to optimize thermal management for high-power applications. The **Error! Reference source not found.** provides a comprehensive overview of recent works in immersion cooling, highlighting the type of cooling (single-phase or two-phase), the unique contributions of each study, and the specific challenges they address.

Table 2 Summary of Recent Studies on Immersion Cooling

Author	Year	Type	Uniqueness	Challenge Addressed	References
Yang Li, et al.	2022	Two-Phases	SF33 dielectric liquid with two-phase boiling was used for better temperature control compared to forced air cooling under various discharge conditions.	Managing aggressive boiling dynamics at high C rates.	[45]
Kathan Gajjar, Huei-Ping Huang	2023	Single-Phase	Introduced a loop filled with a dielectric liquid driven by thermal convection without a fan/pump, using Tesla valves to enhance directional flow.	Improving convective flow efficiency and maintaining unidirectional flow without active components.	[80]
Liqun Zhou, et al.	2024	Two-Phase	Investigated using methanol as a coolant for two-phase immersion cooling of high-power electronics with CFD simulations.	Boiling instability and optimizing mass flow rate and temperature for best cooling performance.	[81]
Cheng Liu, Hang Yu	2021	Two-Phase	Analyzed coefficient of performance (COP) and partial power usage effectiveness (pPUE) for various IT loads using CFD and experiments.	Finding the optimal server spacing and managing exergy destruction in a high-density setup.	[82]
Aleksandar Ristic-Smith, Daniel J. Rogers	2024	Two-Phase	Demonstrated improved heat transfer using grit-blasting and pin fin modifications in a sealed dielectric fluid enclosure for PCB power electronics.	Dealing with system complexity due to heat exchangers and maintaining high critical heat flux.	[83]
Sergio Perez	2021	Two-Phase	Optimized Edge Computing scenarios with energy-aware strategies using two-phase immersion cooling and smart resource allocation via Deep Reinforcement Learning (DRL).	High implementation costs and efficient system design to manage Edge Data Centers in urban areas.	[84]
Baris B. Kanbur	2020	Two-Phase	The proposed hybrid cooling and energy	Integrating waste heat utilization effectively	[78]

			generation system combines two-phase immersion cooling and a PEM fuel cell for enhanced energy utilization.	and optimizing the hybrid system for better exergy performance.	
Wei Tong	2022	Two-Phase	Experimental temperature-dependent boiling heat transfer coefficients were used in numerical modeling to analyze the heat spreading effect for immersion cooling.	Achieving uniform temperature distribution and minimizing the critical heat flux region to avoid dry-out.	[85]
Yongping Huang	2024	Single-Phase	Examined different flow directions and control charts for coolant properties to optimize single-phase immersion cooling performance for data center servers.	Flow optimization and managing coolant viscosity effects on performance.	[86]
Po-Yao Lin	2024	Two-Phase	Applied two different boiler designs for two-phase immersion cooling of 2.5D/3D heterogeneous integration packages, achieving lower junction-to-ambient thermal resistance.	Ensuring optimal thermal performance for high-power, high-density chip packages.	[87]
Chady Al Sayed	2021	Two-Phase	Introduces a multi-scale electroplated porous coating for CPUs, enhancing boiling performance.	Cost of redesigning servers, chemical compatibility of dielectric fluids, and managing choking effects in gravity-driven flows.	[36]
Xueqiang Li	2023	Single-Phase	Multi-parameter optimization for server performance, considering interactive effects of fin height, spacing, and flowrate.	Complexity in optimizing multiple interacting parameters and managing pressure loss.	[88]
Ce Zhang	2023	Two-Phase	Proposed a multi-mode condenser system for energy efficiency across various climate conditions.	Higher operational costs for certain dielectric fluids, dependency on local climate for cooling effectiveness.	[89]
N.P. Williams	2023	Two-Phase	Examines the benefits of immersion cooling for	Maintaining thermal homogeneity during	[90]

			high C-rate charging and discharging of lithium-ion batteries.	vigorous boiling conditions and managing fluid saturation temperatures.	
N.P. Williams	2024	Two-Phase	Focuses on the performance of closely spaced battery cells under different immersion cooling conditions.	Difficulty in achieving desired thermal uniformity with high power densities.	[91]
Cheng Liu, Hang Yu	2022	Two-Phase	Developed a prediction model for saturated boiling heat transfer coefficients in CPUs, providing insights into energy conservation.	Managing temperature limits and ensuring CPU frequency does not decrease under high-density heat dissipation.	[92]

The deposition of nano particles in the dielectric also enhanced the pool boiling heat transfer [93]. These nano particles induced dielectric fluids can enhance the PUE by delivering a maximum heat transfer coefficient [94]. Luo et al. investigated the use of SiC nanoparticles in white mineral oil for immersion cooling, finding that the nanofluid increased the surface heat transfer coefficient by 11.3%, making it an effective cooling medium for high-density heat loads [95]. Niazmand et al. performed a numerical analysis of immersion cooling using Al_2O_3 nanofluid in mineral oil, demonstrating improved thermal conductivity and a reduction in CPU temperature by up to 3.72°C at 5% mass concentration of nanoparticles [96].

Another significant trend is the integration of two-phase immersion cooling into various high-density and high-power systems, including data centers, and even edge computing environments [97]. In the context of data centers, researchers have been exploring how multi-parameter optimization such as fin spacing, height, and flow rates can help enhance server performance while maintaining the efficiency of cooling systems [39]. The focus here is on maintaining a uniform temperature distribution and preventing overheating during aggressive operations [98]. In electric vehicles, cooling batteries is a big challenge [99]. For lithium-ion batteries, two-phase immersion cooling is being tested for applications involving rapid charging and discharging cycles, such as electric vehicles [100].

Studies have also delved into the potential of using predictive models to estimate the heat transfer coefficients, making it easier to design systems that can maximize cooling performance while minimizing energy consumption [101]. The use of deep reinforcement learning [102] to optimize cooling strategies for edge computing is another emerging trend that reflects the push towards smart, adaptable cooling solutions that can respond dynamically to changing computational loads and thermal conditions [103]. Suh et al. introduced a deep learning framework utilizing convolutional neural networks (CNNs) to predict boiling heat transfer by analyzing dynamic bubble behavior, achieving an average prediction error of just 6% [104]. Sajjad et al. developed a deep neural network (DNN) to estimate the pool boiling heat transfer coefficient for porous surfaces used in immersion cooling systems, providing a high prediction accuracy with an R^2 value of 0.976 [105].

These advancements reflect a broader trend towards leveraging machine learning, advanced simulation, and optimization techniques to overcome the challenges inherent in two-phase immersion cooling, such as fluid management, phase-change dynamics, and pressure regulation.

5. CHALLENGES

Immersion cooling, while offering significant thermal management benefits, can be costly to implement and maintain. The initial setup often requires specialized equipment and infrastructure, including immersion tanks, dielectric fluids, and monitoring systems, which can incur high upfront expenses [106]. Additionally, ongoing maintenance, such as fluid replenishment, equipment removal for servicing, and potential repairs due to leaks or spills, further adds to the operational costs. Further, submerging the heat-generating components of the server in the dielectric fluid may introduce reliability concerns at the device level [107]. One significant challenge is fluid selection and compatibility. The dielectric fluids used in immersion cooling must not only have excellent thermal properties but also be chemically stable, non-corrosive, and environmentally safe [108]. Vapor management is another critical issue, particularly in two-phase systems where the generated vapor must be effectively condensed and reintroduced into the system.

6. CONCLUSION

In conclusion, immersion cooling presents a compelling solution to the growing challenges of thermal management in modern computing environments. With its ability to efficiently dissipate heat, reduce energy consumption, and enhance hardware reliability, immersion cooling offers a promising alternative to traditional air-based cooling methods. Despite its initial cost and maintenance considerations, immersion cooling has the potential to revolutionize data center operations by improving performance, reducing operational costs, and minimizing environmental impact. As the demand for high-performance computing continues to rise, immersion cooling stands out as a viable and innovative solution to meet the evolving needs of the digital age. In future research endeavors focused on design, development and commissioning of immersion cooling platforms, there is significant potential for refinement and innovation. Various aspects of these technologies can be optimized to enhance their effectiveness, efficacy and widen the range of their applicability. Based on the various aspects explored in this review, a few of the opportunities and endeavors for future developments for fortifying immersion cooling platforms are identified below:

1. Explore potential for the deployment of advanced coolants (e.g., nanofluids) with enhanced thermal conductivity and dielectric properties to further improve the efficiency of heat transfer while ensuring safety for electronic components with minimal environmental footprints (e.g., for better sustainability).
2. Investigate energy-efficient vapor management techniques, particularly for reducing the pumping costs required to cool down vaporized bubbles of the coolant, focusing on novel heat exchanger and condenser designs (e.g., using nanoparticle doped paints for minimizing fouling and corrosion).
3. Utilize deep learning algorithms to predict system behavior, optimize boiling dynamics, control heat transfer processes, and anticipate cooling requirements based on fluctuating workloads.

4. Develop scalable immersion cooling designs that can be efficiently implemented in hyperscale data centers, ensuring consistent thermal performance across high server densities while maintaining ease of installation and maintenance.
5. Explore hybrid cooling systems that integrate two-phase immersion cooling with direct-to-chip or air-assisted cooling to maximize cooling efficiency and adaptability, particularly in high-performance and variable workload environments.
6. Employ IoT sensors and AI-driven analytics for real-time monitoring and adaptive control, allowing immersion cooling systems to maintain optimal thermal conditions and minimize energy usage dynamically.
7. Work towards establishing industry standards and best practices for immersion cooling, facilitating broader adoption by ensuring compatibility, reducing operational risks, and promoting consistent system design and implementation.
8. Explore the deployment of Thermal Energy Storage (TES) platforms for load balancing and thermal management, e.g., using Phase Change Materials (PCM), that can enable reduction of water usage in data centers for enhanced sustainability, reliability, robustness, reliability and resilience.

These efforts mentioned above can be geared towards realizing the aims and goals for establishing immersion cooling as a viable and sustainable solution for implementing energy efficient (and water efficient) thermal management platforms in various applications, including data centers, and electronics cooling. Such platforms can then be translated for adaptation in other applications, such as in renewable energy systems (e.g., geothermal energy, nuclear energy, solar-PV and solar thermal power plants) as well as solar thermal desalination systems (e.g., thermal desalination systems that can be integrated with waste heat recovery from data centers by using an intermediate TES platform).

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