2019-9

A Techno-Economic Analysis of Current Cooling Techniques in Irish Data Centres

Lee Gibbons

Technological University Dublin, c15486098@mytudublin.ie

Bryan Coyne

Trinity College Dublin, Ireland, brcoyne@tcd.ie

David Kennedy

Technological University Dublin, david.kennedy@tudublin.ie

See next page for additional authors

Follow this and additional works at: <https://arrow.tudublin.ie/engschmanart>

Part of the [Energy Systems Commons](#), and the [Heat Transfer, Combustion Commons](#)

Recommended Citation

Gibbons., L, Coyne, B., Kennedy, D., Alimohammadi, S. (2019). A techno-economic analysis of current cooling techniques in Irish data centres. *Proceedings of the 25th INTERNATIONAL WORKSHOP on Thermal Investigations of ICs and Systems, Thermnic 2019*

This Conference Paper is brought to you for free and open access by the School of Manufacturing and Design Engineering at ARROW@TU Dublin. It has been accepted for inclusion in Articles by an authorized administrator of ARROW@TU Dublin. For more information, please contact arrow.admin@tudublin.ie, aisling.coyne@tudublin.ie, gerard.connolly@tudublin.ie.

Funder: School of Mechanical and Design Engineering, Technological University of Dublin for the Research Action Plan (RAP)

Authors

Lee Gibbons, Bryan Coyne, David Kennedy, and Sajad Alimohammadi

A Techno-Economic Analysis of Current Cooling Techniques in Irish Data Centres

Lee Gibbons¹, Bryan Coyne², David Kennedy¹, Sajad Alimohammadi^{1,3,*}

¹ School of Mechanical and Design Engineering, Technological University Dublin, City Campus, Ireland

² Department of Economics, Trinity College Dublin, Dublin, Ireland

³ Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Dublin, Ireland

* Corresponding Author: sajad.alimohammadi@tudublin.ie, +353 1 402 3900

Abstract

This research is part of a comprehensive study to determine reformative actions for cooling regimes within the Irish data centre market. To achieve this goal, preliminary Exergy, Entropy change and operational cost analyses are used. It is determined that there is no clear advantage for using one cooling method over another without knowing the data centres secondary function (e.g. district heating, energy generation). Air cooling technology is a good candidate for a highly reliable system due to the low exhaust temperatures of 30°C. Two-phase immersion is a possibility for economically viable data centres where operational costs are to be minimised, although the capital expenditure could outweigh operational expenditure. Hybrid cooling has a low waste heat rate of 2.569 kJ/s, slightly above the lowest waste heat from the passively cooled two-phase immersion cooling at 2.5 kJ/s. Hybrid cooling benefits from the combination of concentrated hot spot cooling and general air cooling has an Entropy change of 0.009 kJ/K.

1 Background

Data centres in Ireland consume approximately 15% of the nation-wide generated electricity. This makes Irish data centres responsible for approximately 1.72 billion tonnes of CO₂ per year from the consumed electricity on the Irish grid (calculated in using eq. (1)). Data centres are essentially a warehouse facility in which there are several racks that store servers. These servers can be used as data storage, computing power with switchgear, etc., where the requirement for cooling stems from. On average, data centre cooling consumes up to approximately 40 % of the total input electricity from global surveys on the market [1]. Assuming an average cooling electricity utilisation in Ireland, therefore Irish data centres cooling is responsible for 682.9 million tonnes of CO₂ per year. It is important to note, that Ireland has a higher proportion of hyperscale data centres thus estimated carbon emission can be lower. This is due to hyperscale data centres not requiring marketing for users (Uptime institutes tier operation classification is marketable for colocation wholesalers) as the data centre is owned, operated and used by the same user thus the parameters for cooling can be changed independently from ASHRAE TC9.9 or NEBS standards. In addition, hyperscale data centres also use more efficient cooling and thus lower PUE scores in general.

The literature on Irish data centres is concerned on net electricity consumption. There is a high penetration of data centres in Ireland with a 55% increase in planned or under construction data centres [2]. There is a requirement for metrics like PUE to be consolidated to drive energy efficiency within Irish data centres. The introduction of I-SEM (Integrated Single Electricity Market), promotes the shift from fossil-based electricity sources to renewables and has placed a more positive driving force on consumers.

This paper is the first part of a comprehensive study on the Irish data centre landscape. This paper addresses three commercial cooling options and their effectiveness

particularly on energy management with the following objectives:

1. Provide a brief background on the Irish data centre market landscape.
2. Perform a preliminary comparison between the three core cooling options using energy removal, recovery, and electricity usage.
3. Carry out a comparative analysis of the operational cost of each cooling technique.

1.1 The Irish data centre landscape and its energy use

Many multinational technology companies have significant investments in Ireland; recent market changes to cloud-based services has led to many data driven investments in utilities and employees. Climate has been cited as one of the specific reasons for data centre investment in Ireland as 80% of the year the temperature is below 27°C thus free air economiser can effectively be used to cool the data centre. This is similar to Scandinavia, Northeast Europe and the UK [3].

There are currently 53 operational data centres in Ireland and an additional 29 in construction or planning [2]. The breakdown by percentage of capacity is 72% hyperscale (builder, operator, and consumer are the same company), 13% colocation wholesale (operator and consumer are the same, outsourced building), 12% colocation (building and operator are the same, user is different company), 3% private (operator and consumer are the same, outsourced building). 0% edge (interface data centre focused on networking, e.g. 5G) [2]. This is graphically shown in Fig. 1.

Eq. (1) determines the percentage of total grid power in Ireland dedicated to data centres which equates to 3.94 TWh per annum. This is calculated using the operational uptime percentage per year (capacity factor - C_{factor}) of 0.75, similar to the modelling methods of Coyne *et al.* [4] and Eirgrid [5].

Figure 1 Types and size of data centres in Ireland [6]

The maximum grid power demand (P_{dc}) for data centres in Ireland used in this estimation is 600 MW, taken from the first quarterly 2019 Host in Ireland report [2]. The total grid power demand for Ireland ($P_{Ireland}$) in 2018 was 26 TWh [6].

$$P_{\%} = \frac{P_{dc} \times C_{factor} \times 8760 \text{ hr}}{P_{Ireland}} = 15.16\% \quad (1)$$

The 3.94 TWh can be multiplied by the carbon dioxide intensity average for Ireland's power sources which is 0.437 kgCO₂/kWh [6]. As a result, the total current emissions from this market is approximately 1.723 billion tonnes of CO₂ per year.

Power Utilisation Equation (PUE) is the total load into the data centre divided by the IT load used by electronic computing and processing equipment [7]. The optimal PUE score is 1.0. The PUE equation is shown in Eq. (2).

$$PUE = \frac{\text{Total load}}{\text{IT load}}; PUE \geq 1 \quad (2)$$

2 Cooling technologies

The three cooling options considered are shown in Fig. 2. It highlights the variety in the methods and the coolants interactions with the heat source (electronics).

Figure 2 Three commercial cooling options

2.1 Air cooling

Air cooling relies on using fans to pass air through the server rack. This method is the most popular in Irish data centres due to the low ambient temperatures. In the EU, a survey of 289

data centres in 2017 concluded: 170 had no free cooling options, 78 used one type of free cooling, and 41 used a combination of two or more free cooling options [8].

ASHRAE TC9.9 is an industry standard as a guideline of best practice and outlined several classes of thermal guidelines for operators and manufacturers. Note that in the standard, temperatures are defined as inlet air temperatures. Classes A1 to A4 are the recommended classes, with the general range class for the upper band of 18°C to 27°C, a lower band of -9°C to 15°C, and 50% relative humidity [9]. Other standards are NEBS and ETSI. The European Union (EU) in 2018 published the best practice guidelines for the EU code of conduct on data centre energy efficiency. The EU set the inlet coolant air range 10°C to 35°C in accordance with ASHRAE class A2 as the standard to be met [10]. It is defined as the bracket for optimal energy savings. ASHRAE class A1 is defined as inlet coolant range of 15°C to 32°C as a lower class, but some legacy systems may still operate in this range [10]. It could be concluded that due to the growth in the Irish data centre market being recent, most systems are not legacy and are ASHRAE class A2 compliant.

2.2 Two-phase liquid immersion cooling

There are two main configurations of immersion cooling, bath (two-phase) and enclosure (mostly single-phase). The more common immersion cooling system is bath; this is called two-phase as the dielectric liquid boils and then condenses causing convection currents while the boiling of the dielectric removes the heat. The Open Computer Project (OCP) is a crowd-sourced standard and is ongoing. This means that the standard operation of an immersion data centre is unclear as of yet as all immersion data centres would thus be required to operate off their own research and development, not a standard.

2.3 Hybrid (air/liquid) cooling

Hybrid cooling relies on concentrated hot spot cooling using surface contact and general airflow to cool the rest of the CPU board. Generally, the CPU is the targeted area as determined

by Ebrima *et al.* (2014). It is the highest temperature component and thus is a prime target for water cooling. There are two main configurations for hybrid cooling. In-rack cooling and centralised distribution unit.

There are no standards yet due to the technology's low market adoption and relatively high adoption cost (air cooling and water cooling requirements).

3 Methodology

3.1 Reliability modelling

Reliability of a server can be determined using several variables, such as temperature and coolant linked failures. Coolant linked failure data was not available although temperature linked failure data was available from ASHRAE TC9.9 standard [9]. It is important to note that this model only applies to ASHRAE standard compliant data centres and thus hyperscale data centres for example (or any data centre) can have varying results due to variance from the standard. ASHRAE data indicates the standard operation is 1 (this is the index baseline at 20°C) while the X-factor is the multiplier for increasing or decreasing temperature [9]. 1000 servers were chosen as an arbitrary number to represent the scalability of the problem.

3.2 Thermodynamics study

Assumptions made for the thermodynamic model are to simplify the model for an overall view of the whole market. For the air and hybrid cooling systems, the assumptions are: (1) Steady-state thermal and flow properties. (2) The heat generating components have no heat loss to surrounding areas other than the coolant; to minimise heat transfers calculations. (3) There is no Entropy generation as the system is reversible. (4) The system is open loop, as there is a mass transfer between the rack and surrounding.

For the two-phase immersion, the above assumptions (1-3) are valid and in addition to that: (4) At inlet conditions the dielectric fluid is a liquid (operates at the fluids boiling point); at outlet the fluid is a gas (operates at the fluids boiling point +1°C) (5) The data centre is isolated (thus no lighting load or losses in power delivery systems, to achieve the lowest possible PUE score) and therefore all excess power is for cooling. The assumptions can be summarised as there is no losses of heat other than through the coolant and that the racks run under ideal conditions. (6) Two-phase cooling is a closed loop; this is assumed as the atmospheric conditions do not affect the two-phase cooling performance. In addition, in closed loop systems, there is no mass exchange from the bath of dielectric to the external surrounding.

3.2.1 Entropy change model

Steady open-loop Entropy change uses $\Delta s = Q/T_{avg}$ [11] where s is Entropy (kJ/s.K), Q is the heat flow rate (kJ/s), and T_{avg} is the average temperature across the server (K). This, in turn, becomes eq. (3) where: $\dot{m}$ is the mass flow rate of the coolant (kg/s), C_p is the specific heat capacity of the coolant (kJ/K), T_{out} and T_{in} (K) are the outlet and inlet temperatures

for the coolant, respectively. The mass flow rate will vary as the temperature of the inlet air and the IT load vary. All flow rates were assumed to use the same density of air as the possible variation in inlet temperatures was small when compared to the density changes. The air inlet flow rates were averaged to account for this.

$$\Delta s = \frac{\dot{m}C_p(T_{out}-T_{in})}{T_{avg}} \quad (3)$$

3.2.2 Exergy study

Exergy is defined as the maximum available work that can be extracted from the dissipated heat out of the server by the coolant. The basis for the Exergy study is $B = Q \cdot (1 - T_{in}/T_{out})$. For an open-loop system, the calculated Exergy is shown in eq. (4).

$$B = \dot{m}C_p(T_{out} - T_{in}) \left(1 - \frac{T_{in}}{T_{out}}\right) \quad (4)$$

3.3 Economic outcome

This section considers financial changes if every data centre adopted a new cooling technology in 2019. It is assumed within only the economics portion that there is an IT load of 5 kW per rack, as described by Coyne *et al* [4] and Eirgrid's [12] studies. Thus, it is calculated that Ireland has approximately 123,471 racks using the above parameters and the calculated electricity usage of Irish data centres.

4 Results

4.1 Reliability due to temperature increases

If one assumes a data centre with 1,000 servers operates at 20°C and allowing for a failure rate of 2% per annum. This means each year there will be 20 failed servers. The same data centre at 25°C will have an X-factor of 1.24 which means it the failure rate now is $(2 \times 1.24) \times 10 = 24.8$ so the failure rate has risen from 20 to 25 servers per annum for a 5°C increase in temperature. The temperature data alone would indicate a preference for lower temperature.

Figure 3 Failure rate for 1000 servers

In this reliability model, the lower band failure rate was assumed to be 2% and the upper band to be 5% this was similar to the green grid's assumption of 2% and 4% [3]. The additional 1% on the upper limit is to account for the failure of the cooling system to cause a cascade failure to the server. This model is shown in Fig. 3.

4.2 Thermodynamics study

4.2.1 Air Cooling

The parameters are outlined in

Table 1. The temperatures used are from the work done by Capozzoli et al. (2015) as there were several data centres surveyed. These parameters were determined to be the standard for Ireland and the United Kingdom [13]. Flow rates are a difficult parameter to survey as the flow rate generally changes depending upon rack temperature and can change from rack to rack or server to the server thus it was averaged using other research studies. The flow rates were: $0.226 \text{ m}^3/\text{s}$ according to Bai et al. (2018) [14], in the range of 0.26 to $0.54 \text{ m}^3/\text{s}$ according to Wang et al. (2015) [15], $0.7 \text{ m}^3/\text{s}$ according to Wibron et al. (2016) [16], and in the range of 0.09 to $1.18 \text{ m}^3/\text{s}$ according to Ebrahimi et al. (2014) [17]. All values are within a range of 0.09 to $1.18 \text{ m}^3/\text{s}$ with an average of $0.499 \text{ m}^3/\text{s}$. To determine the mass flow rate, an air density of $1.191 \text{ kg}/\text{m}^3$ at 23.5°C [18] was extrapolated; -giving a mass flow rate of $0.595 \text{ kg}/\text{s}$. The specific heat capacity is $1.00475 \text{ kJ}/\text{kg } ^\circ\text{C}$, extrapolated from thermodynamic steam tables by Rogers et al. at a mean temperature of 23.5°C [18]. Temperature inlet and outlet are shown in Table 1, subscript a is for air.

Table 1 Air cooling data centre study parameters

Notation	Value	Units	Source
$T_{in a}$	290.15	K	[13]
$T_{out a}$	303.15	K	[13]
$C_{p a}$	1.00475	$\text{kJ}/\text{kg } ^\circ\text{C}$	[18]
m_a	0.595	kg/s	[17], [19], [15], [16]

Table 2 shows the results calculated from the data in Table 1 and eqs. (3, 4). Using these parameters, the Entropy change within the coolant is determined, in addition to the maximum available work and total waste heat rate for air cooling (Q).

Table 2 Calculated results for air cooling

Parameter	Value	Units
Waste heat rate	7.768	kJ/s
Δs	0.026	kJ/K
Available work (Exergy)	0.333	kJ

4.3 Two-phase immersion

The assumptions outlined allow for the PUE score to be used to determine waste heat rate within the data centre; from this, the Entropy change and Exergy can be calculated using the open-loop calculations. Subscript d is for two-phase parameters. The system parameters are shown in Table 3.

Table 3 Two-phase cooling data centre study parameters

Notation	Value	Units	Source
PUE	1.01		[20]
$IT \text{ load}$	250	kW	[20]
$T_{boil d}$	335.15	K	Assumed
$T_{amb d}$	334.15	K	[21]

The results using the parameters above are shown in Table 4.

Table 4 Calculated results for two-phase cooling

Parameter	Value	Units
Waste heat rate	2.5	kJ/s
Δs	0.041	kJ/K
Available work (Exergy)	0.040	kJ

4.3.1 Hybrid Systems

Hybrid cooling uses water and air. When calculating waste heat rate, Entropy change and Exergy, it was calculated separately for air and water and added to give the total cooling system results. The system parameters are shown in Table 5.

Table 5 Hybrid cooling data centre study parameters

Parameter	Notation	Value	Units	Source
Temp. inlet	$T_{in w}$	303.15	K	[22]
Temp. outlet	$T_{out w}$	308.15	K	[22]
Specific heat capacity	$C_{p w}$	4.178	$\text{kJ}/\text{kg } ^\circ\text{C}$	[18]
Mass flow rates	m_w	0.03	kg/s	[22]
Temp. inlet	$T_{in b}$	297.15	K	[22]
Temp. outlet	$T_{out b}$	301.15	K	[22]
Specific heat capacity	$C_{p b}$	1.0047	$\text{kJ}/\text{kg } ^\circ\text{C}$	[18]
Mass flowrates	m_b	0.483	kg/s	[22]

The results shown in Table 6 are the summed results for water and air flows. In terms of individual results for air and water, waste heat rate was $0.627 \text{ kJ}/\text{s}$ and $1.942 \text{ kJ}/\text{s}$, respectively.

Table 6 Calculated results for hybrid cooling

Parameter	Value	Units
Waste heat rate	2.569	kJ/s
Δs	0.009	kJ/K
Available work (Exergy)	0.036	kJ

4.4 Economics of systems

Based on PUE score alone with mechanical air cooling as the baseline due to its popularity in the industry, the energy consumption per rack and operational expenditure (OPEX) are shown in Table 7.

Table 7 Cost reduction on OPEX per 5 kW rack

	Power (kWh/yr)	OPEX (€)	Cost reduction (%)
Air	60,116	10,220	Baseline
Two-phase	33,179	5,640	44.81
Hybrid	48,618	8265	19.13

5 Discussion of results

5.1 Reliability

The reliability model is solely focused on temperature. Thus, the lowest exhaust temperature within the ASHRAE inlet coolant conditions would indicate the lowest chance of failure specified by the ASHRAE reliability data. The order of preference for cooling technology based on the operational temperature range would be: 1. Air (303.15 K exhaust) 2. Hybrid (308.15 K exhaust) 3. Two-phase immersion (335.15 K exhaust). The coolant linked failures data was not available, these failures are caused by the coolants itself.

5.2 Thermodynamic study

5.2.1 Entropy change

In terms of Entropy change, air cooling is higher than the two other techniques due to the higher flow rate of coolant while having a lower inlet temperature. This indicates a higher waste heat rate per average operating temperature. Fig. 4 shows a comparison of the Entropy change for each system.

Figure 4 Entropy change comparison

5.2.2 Exergy (available work)

Exergy is the maximum available recoverable energy from the waste heat. This is a favourable property. Air cooling is higher than two-phase cooling and hybrid cooling, this is due to the temperature differential between the inlet and outlet being higher than two-phase and hybrid. Where in the air portion of hybrid cooling the specific heat, capacity is the same as air only cooling. The mass flow rate is lower in air hybrid than air only cooling thus the air does less heat

removal in hybrid cooling. This places the heat removal requirement to be done with water in hybrid cooling to offset the lower airflow rates. This is shown in Fig. 5.

Figure 5 Exergy comparison

5.2.3 Waste heat rate

The comparison of the three cooling options is shown, with air cooling waste heat rate of 7.8 kJ/s and Hybrid cooling waste heat rate of 2.569 kJ/s. Although under the bases of low Entropy change and low Exergy, the two-phase immersion cooling would offer minimal recovery, but also has minimal losses as outlined with the low energy loss of 2.5 kJ/s.

5.3 Economics of systems

In the whole Irish data centre landscape assuming every data centre used air cooling at a PUE score of 1.83 [13], the yearly operational expenditure is €693.6 million (assuming €0.17/kWh). Switching to two-phase cooling which has a PUE of 1.01 [23] would have a yearly operational expenditure of € 382.81 million. Hybrid cooling would have a yearly operational expenditure of € 560.94 million (PUE of 1.48 [24]). This indicates that two-phase from an economic standpoint is favoured as it has the lowest OPEX. Ideally, capital expenditure would be calculated although two of the three cooling technologies rely heavily on custom-built fittings. The cooling capital expenditure could not be determined within the scope of this paper.

6 Conclusions

Reliability is the key to all system operations. In terms of isolated temperature reliability, the preference is determined in the lower exhaust temperature for the lower the chance of failure with 1. Air (303.15 K exhaust) 2. Hybrid (308.15 K exhaust) 3. Two-phase immersion (335.15 K exhaust).

Waste heat is to be reduced in order to maximise efficiencies. Due to two-phase immersion cooling being mostly passive with a low PUE, it is not a suitable option for waste heat rate recovery in the bath configuration with no outlets.

The preferred cooling for Entropy change minimalization is hybrid cooling at 0.009 kJ/K. This is due to the combination of air and water allowing for the hot spots to be concentrated on while a low airflow rate can cool auxiliary systems.

For Exergy, the benefits of having a high-temperature system such as two-phase cooling are found to be advantageous. Air cooling has the highest Exergy with its constant gas phase minimises energy lost between phase changes and offers

excellent potential for future energy recovery options such as district heating to utilise the available waste heat.

From an economic perspective, the cheapest option depends on capital expenditure or OPEX minimisation. The most likely candidate for adoption is two-phase due to the low operation cost. While its capital expenditure is theorised to be higher, the OPEX is significantly lower in all states (per rack and per nationwide adoption).

To summarize, if the primary objective of a data centre is to operate as a data centre, and the secondary function is to provide local distributed heating or the system is to be the most reliable, then air cooling is a likely option. If the secondary objective is to be low in running cost, two-phase immersion is a favourable candidate. If the secondary function is to minimize thermal losses while having a low cycle loss, hybrid cooling would be the preferred option. The three cooling methods offer no distinct overall advantage over one another; each method is suited to a specific application. Data centres are 21st century features of society and they can outweigh the high electricity consumption. The efforts on cooling efficiency enhancements can help reduce this negative impact of high electricity consumption for a net positive outcome for the future of data centres.

Acknowledgements

The authors would like to extend their gratitude to the School of Mechanical and Design Engineering, Technological University of Dublin for the Research Action Plan (RAP) bursary funded under the DREs Empowering Schools' Research initiative.

Literature

- [1] J. Ni and X. Bai, "A review of air conditioning energy performance in data centers," *Renewable and sustainable energy reviews*, 2017.
- [2] Host In Ireland, Bitpower, "Ireland's Data Hosting Industry Q1 2019 Update," Host In Ireland, Dublin, 2019.
- [3] S. Strutt, C. Kelley, H. Singh and V. Smith, "DC efficiency and IT equipment reliability at the wider operating temperature and humidity ranges," *The green grid*, 2012.
- [4] B. Coyne and E. Denny, "An economic evaluation of future electricity use in Irish data centres," *Trinity College Dublin (TRiSS)*, Dublin, 2018.
- [5] Eirgrid, "Eirgrid generation capacity statement," 2016.
- [6] Sustainable Energy Authority of Ireland, "Energy in Ireland 2018," SEAI, 2018.
- [7] T. Van De Voort, V. Zavarel, I. T. Galdiz and J. Hensen, "Analysis of performance metric for data centre efficiency," *REHVA*, vol. February, pp. 1-11, 2017.
- [8] M. Avgerinou, P. Bertoldi and L. Castellazzi, "Trends in data centre energy consumption under the European code of conduct for data centre energy efficiency," *Energies*, vol. 1470, no. 10, 2017.
- [9] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Standard TC9.9: Data Center Power Equipment Thermal Guidelines and Best Practices, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2016.
- [10] M. Acton, P. Bertoldi, J. Booth, L. Newcombe, A. Rouyer and R. Tozer, "Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency," European union joint research centre, Luxembourg, 2018.
- [11] J. Garai, "Entropy is a mathematical formula," *arXiv*, 2003.
- [12] Eirgrid, "All-island generation capacity statement 2018 - 2027," Eirgrid, Dublin, 2018.
- [13] A. Capozzoli and G. Primiceri, "Cooling systems in data centers: state of art and emerging technologies," in *7th International Conference on Sustainability in Energy and Buildings*, Torino, Italy, 2015.
- [14] Y. Bai and L. Gu, "Chip temperature-based workload allocation for holistic power minimization in air-cooled data center," *Energies*, vol. 10, no. 12, 2017.
- [15] I.-N. Wang, Y.-Y. Tsui and C.-C. Wang, "Improvements of Airflow Distribution in a container Data center," *The 7th International Conference on Applied Energy – ICAE2015*, vol. 7, no. 75, pp. 1819-1824, 2015.
- [16] E. Wibron, A.-L. Ljung and T. S. Lundstrom, "Comparing performance metrics of partial aisle containments in hard floor and raised floor data centers using CFD," *Energies*, vol. 12, no. 1473, 2019.
- [17] K. Ebrahimi, G. F. Jones and A. S. Fleischer, "A review of data center cooling technology, operating conditions and corresponding low-grade waste heat rate recovery opportunities," *Renewable and Sustainable Energy Reviews*, vol. 31, pp. 622 - 638, 2014.
- [18] G. Rogers and Y. Mayhew, *Thermodynamics and transports properties of fluids*, 1996: Blackwell publishing, fifth edition.
- [19] B. Yan, G. Lijun and Q. Xiao, "Comparative study of energy performance between chip and inlet temperature-aware workload allocation in air-cooled data center," *Energies*, vol. 11, no. 669, 2018.
- [20] 3M Novec engineering fluids dept., "Two-phase immersion cooling: a revolution in data center efficiency," 3M, US, 2015.
- [21] American Society of Heating, Refrigerating and Air-Conditioning Engineers, "2011 Thermal Guidelines for data processing environments - expanded data center classes and usage guidelines," ASHRAE, 2011.
- [22] A. Carbo, E. Oro, J. Salom, M. Canuto, M. Macias and J. Guitart, "Experimental and numerical analysis for potential heat reuse in liquid cooled data centres," *Catalonia Institute for Energy Research (IREC)*, Barcelona, 2016.
- [23] A. Controls, "DataTank™ Container Unit 1.4MW," 3M, 2014.
- [24] Y. Q. Chi, J. Summers, P. Hopton, K. Deakin, A. Real, N. Kapur and H. Thompson, *Case study of a data centre using enclosed, immersed, direct liquid-cooled servers.*, Leeds: White Rose University Consortium (uni. of Leeds), 2014.