Classification of Jet Impingement Solar Collectors – A Recent Development in Solar Energy Technology

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Abstract- Jet impingement mechanism has been extensively studied in previous research due to its ability to enhance the efficiency of a solar collector. The photovoltaic module temperature can be effectively lowered while preserving the temperature uniformity and enhancing the solar collector performance. Since jet impingement offers such a broad application, numerous studies have focused on its heat transfer characteristic. This article provides a comprehensive review of recent jet impingement solar collectors. Additionally, the design and performance of the jet impingement cooling methods on solar air collectors, photovoltaic and photovoltaic thermal systems are discussed. The comprehensive review is classified into four main components involving jet impingement in solar collector applications: single pass, double pass, concentrated and jet configuration. A critical review is discussed at the end of each classification. The nozzle streamwise and spanwise pitch, nozzle to target spacing, nozzle diameter, nozzle shape, and Reynold number significantly impact the heat transfer properties of jet impingement. Research on applying single pass-single ducts using jet impingement is still lacking and needs further research. Thermally, a double pass-solar collector outperforms a single pass-solar collector due to the absorber plate's high heat extraction rate and more significant interaction caused by the doubled heat transfer surface.

Keywords Jet Impingement, Photovoltaic, Photovoltaic thermal, Solar collector, Efficiency

1. Introduction

The increasing need for energy in both industrial and domestic use has sparked a desire for renewable energy as an alternative to fossil fuels [1]. Renewable energy sources have emerged as a feasible substitute for conventional energy sources, particularly photovoltaic technologies, because of the abundant solar energy [2]–[4]. Solar energy is the least expensive, most plentiful and environmentally benign type of renewable energy that can be used for power generation and heating [5]–[7]. Due to climate change, many countries are searching for a more environmentally friendly and sustainable technologies that could substitute fossil fuels [8]–[10]. Concurrently, the World Green Building Council (WGBC) has introduced a new goal to cut greenhouse gas emissions by 40% and reach 100% net zero-emission building by 2050 [11].

Compared to other forms of energy, the technology behind solar energy, known as photovoltaic (PV) and photovoltaic thermal (PVT) technology, has several benefits and drawbacks [12]. Among the drawbacks of solar technology is the fact that they heat up due to being exposed to sun rays to generate power, thus indirectly reducing the efficiency of the solar collector [13]. Much research has been done focusing on the cooling method of solar collectors to lower the operating temperatures, thus improving the efficiency performance. The cooling mechanism in solar collectors is a significant factor in maximizing the solar collector's efficiency [14], [15]. Previous studies have found that the jet impingement method can enhance a solar collector's performance [16]. Numerous industrial applications use impinging jet technology, including cooling turbine blades, annealing metal, chilling electronics, and solar collector cooling. Since jet impingement offers such a broad

Nomenclature

D	Inner print base diameter	*Abbreviations*	
D_d	Distance of discrete rib	BiPVT	Bifacial photovoltaic thermal
D_{IR}	Relative impingement round jets diameter	CFD	Computer Fluid Dynamics
D_o	Outer diameter of inside conical ring	CPC	Compound parabolic concentrator
H_r	Height of discrete rib	CPV	Concentrated photovoltaic
H_R	Height of inside conical ring	CPVT	Concentrated photovoltaic thermal
L_v	Length of discrete rib	Exp	Experimental
T_a	Temperature of air	GTC	Glazed transpired air solar collector
T_b	Temperature of insulation backboard	HCMJPV	High-concentrator multi-junction photovoltaic
T_c	Temperature of transparent cover	HCPVT	High-concentrator photovoltaic thermal
T_p	Temperature of absorber plate	Theor	Theoretical
		PV	Photovoltaic
Greek		PVT	Photovoltaic thermal
α_a	Angle of arc		
g_w	Gap of discrete width		
η_{exe}	Exergy efficiency		
η_{elec}	Electrical efficiency		
η_{th}	Thermal efficiency		
η_{PVT}	Photovoltaic thermal efficiency		

application, numerous studies have focused on its heat transfer characteristic [17]. This paper is a comprehensive review of previous studies on jet impingement methods on solar air collectors, photovoltaic and photovoltaic thermal. Fig. 1 illustrates the flow and structure of the review paper.

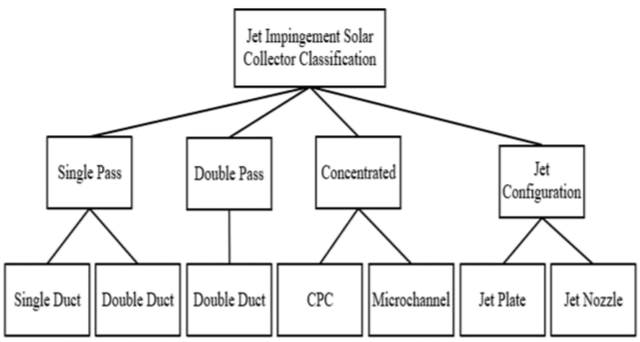

Fig. 1 The general structure discusses in the present review according to jet impingement collector classification.

The jet impingement solar collector is categorized into four main classifications: single pass, double pass, concentrated and jet impingement configuration. The design and performance of the solar collector employing jet impingement methods are discussed according to the classification shown in Fig. 1. A critical review is discussed at the end of each classification. A summary table of previous study efficiency performance of jet impingement methods applied in solar application is presented in the conclusion section.

2. Single Pass Jet Impingement

2.1. Single Pass-Single Duct

Previous comparative research on single-pass solar collectors has discovered enhanced performance under natural convection [18]. The basic fundamental of a single duct is that air is distributed through a single inlet and passes through a single duct, as illustrated in Fig. 2. (a). Previous studies lack the application of single pass-single duct using jet impingement as the fundamental of jet impingement requires a high-speed mass flow rate distributed by jet plate or jet nozzle. By adding a jet plate between the back plate and solar PV, the concept of a single duct will be converted to a double duct, as shown in Fig. 2(b). Thus, there is a lack of research on jet impingement applications in single-duct solar collectors.

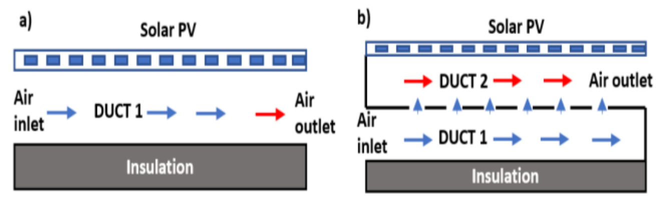

Fig. 2 General cross-section view of (a) single pass-single duct and (b) single pass-double duct.

2.2. Single Pass-Double Duct

Double duct solar collector is preferable to a single-duct collector as the double-duct performs better thermally and electrically [14]. The operating flow state significantly impacts the solar collectors' thermal efficiency. Regarding thermal performance, heat removal rate and temperature gain are directly proportional [19]. The heat transfer coefficient between the air stream and the absorber plate is an essential component of a solar collector [20]. The fundamental of a single-pass double-duct solar collector is illustrated in Fig. 3. Air enters duct 1 and is then distributed along duct 2. This subtopic will review previous research on the single pass-double duct jet impingement method employing obstacles such as dimple surfaces, corrugated plates, ribs, fins, and conical rings.

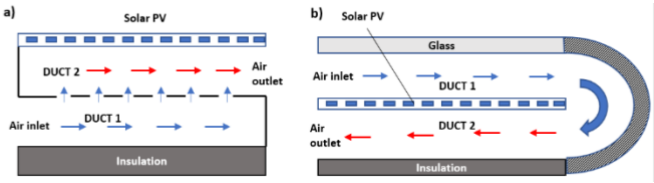

Fig. 3 General cross-section view of (a) single pass-double solar PV at the top duct (b) single pass-double duct solar PV between the glass plate and back-plate insulation.

2.2.1. Dimple

Previous studies on jet impingement on dimpled surfaces have shown a high heat transfer coefficient, influenced by numerous factors, including turbulence level, nozzle configuration, jet confinement, and stand-off distance [21]. The swirling effect from the turbulence flow produced by the jet impingement is assumed to contribute to the high heat transfer rate [22]. A prior study investigated the efficiency of jet impingement cooling on dimpled surfaces stated that the combination of jet impingement and dimples surface could result in a high heat transfer [23].

A study by Mohammad Salman et al. examines the exergy performance of a solar collector using impinging air jet on a dimple roughed absorber plate, as illustrated in Fig. 4 [24]. Air enters from the inlet with a mass flow rate ranging between 0.01-0.07kg/s. The air will then impinge through the jet plate hole 25mm beneath the dimpled absorber plate. The indented dimples absorb the heat before being cooled by the jet impingement. The design proposed achieved an exergy efficiency of only 2.6%.

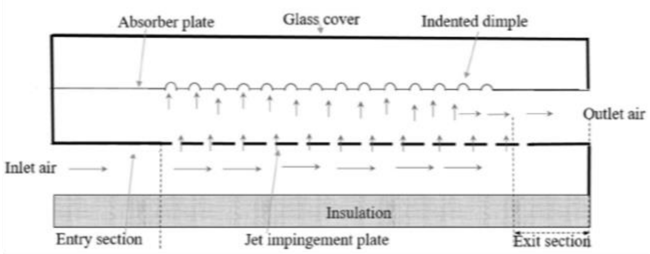

Fig. 4 Cross section of air jet impingement solar collector on a dimple absorber plate [24].

Another study by Mohammad Salman et al. investigates thermohydraulic performance using a similar solar collector design [25]. Artificial roughed dimples were imprinted on the absorber plate to promote a roughness effect on the air flow circumstances, as shown in Fig. 5. According to the experimental setup, the arc angle varies with a range of 30˚-70˚, indented roughness height of 0.016-0.0267mm, and roughness pitch of 0.0269-0.810mm. The result shows that the maximum thermohydraulic achieved was 2.15, with an optimum indented roughness of 0.0267mm.

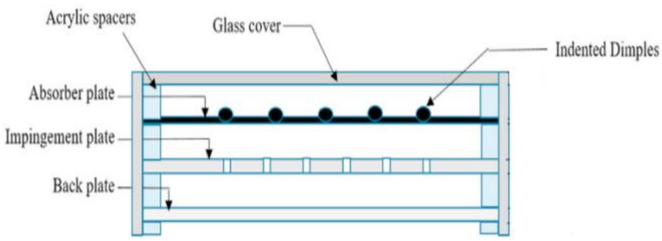

Fig. 5 Cross section of solar heat collector with a single loop and jet impingement over indented dimples [25].

The idea and concept of combining jet impingement with dimple absorber plate is intriguing. The dimpled surface absorbs the heat from the absorber plate, and the jet impingement impinges air to the dimpled surface to cool down the temperature. However, based on the two studies performed by Mohammad Salman et al. observed that the maximum exergy and the thermohydraulic performance were relatively too low. This may be because the dimple size is too small at only 26.7mm. By considering rescaling the dimple size to a more significant dimension, better heat absorption and cooling can occur as it has a more significant surface area. In addition, the energy analysis performance of the study was not mentioned. Thus, it is recommended to conduct an energy analysis performance of a jet impingement with dimple absorber plate.

2.2.2. Corrugated Plate

Using fins or corrugated surfaces is an effective method to enhance heat transfer in a solar collector [26], [27]. The purpose of using a corrugated surface is that it helps to encourage turbulence flow in the air collector, simultaneously increasing the heat transfer while improving the solar collector performance [28]. This method has boosted the solar collector's electrical and thermal performance. However, it can also induce pressure loss in a collector [29].

Alsanossi et al. examined the performance outcome of combining impinging jet mechanism with a corrugated plate in a solar collector [30]. The experimental design is demonstrated in Fig. 6. The mass flow rate, outlet temperature, solar irradiance, and thermal and electrical efficiency are examined. Based on the experiment, the thermal efficiency increases by about 14% at a mass flow rate between 0.01-0.03kg/s. The findings demonstrate that the impinging jet solar collector with a corrugated plate noticeably improves heat transfer. The corrugated plate effectively allows better absorption and improves the heat transfer because of the surface area. The actual length of the corrugated plate can be seen if the plate is straightened. In this case, the length could be the surface area exposed for absorbing/releasing heat.

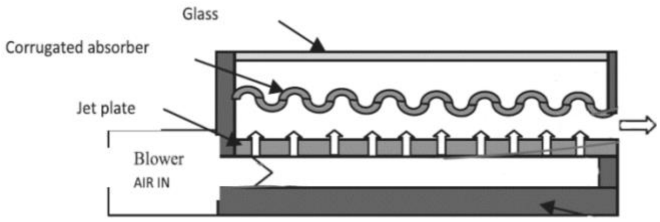

Fig. 6 Schematic diagram impinging jet solar collector with corrugated plat [30].

A study by Zheng et al. established a glazed transpired solar air collector (GTC) with corrugated plate perforating to utilize a jet impingement solar collector [31], [32], as shown in Fig. 7. The collector thermal performance was predicted using energy balance equations. The study stated that the thermal performance achieved was more than 60%. However, the study uses natural convention with 2m/s as the highest velocity recorded. With the large-scale collector measuring 2m in length and 1m in width, it is impossible for the absorber plate acting as a jet impingement to function properly with a low air velocity. To utilize a jet impingement method, high-velocity air is needed to produce the impinging effects. This can only be done using a forced convection method; natural convection is unsuitable for jet impingement as the air velocity is insufficient.

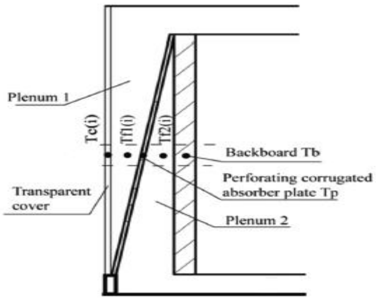

Fig. 7 Schematic view of slit-perforate corrugated plate solar air heater [31], [32]

2.2.3. Ribs

Artificial roughness ribs effectively increase heat transfer by breaching the laminar layer by causing turbulence flow [33]–[36]. Artificial roughness ribs can improve the heat transfer coefficient while minimizing friction [37]. Rahul et al. developed a study on heat transfer and friction enhancement in jet impingement on protrusion rib solar collectors, as shown in Fig. 8 [38], [39]. The experimental findings achieved a 9% increment in Nusselt number and an 11% increment in friction factor.

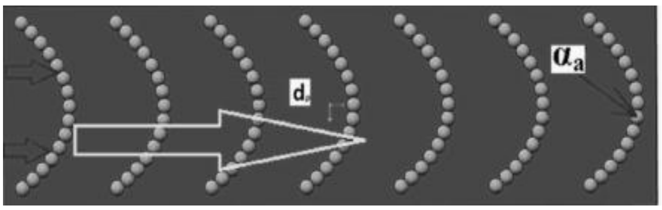

Fig. 8 Protrusion rib absorber plate solar collector [38], [39].

Another study analyses the thermo-hydraulic behaviour of an artificial roughness rib on a jet impingement solar collector [40]. The optimum thermo-hydraulic performance achieved was 1.5. Meanwhile, the effects of the geometrical concept of transverse rib imprinted on an absorber plate jet impingement solar collector were analyzed, as shown in Fig. 9 [41]. The proposed design achieved a thermal efficiency of 78% at a mass flow rate of 0.039kg/s.

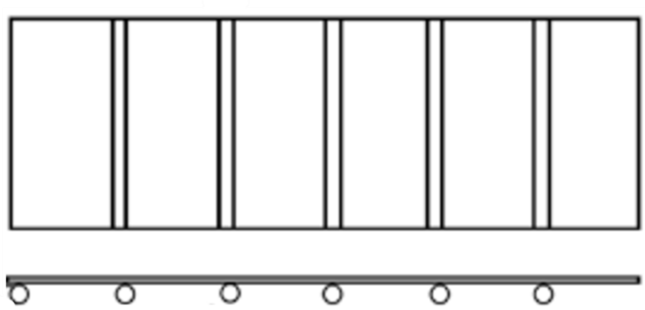

Fig. 9 Transverse rib imprinted on absorber plate [41].

A study by Somayeh et al. performs an exergetic, energetic and economic study to optimize the rib roughness in a solar collector with and without impinging jet [42]. The findings achieved a maximum energy performance of ribs without jet impingement of 58.81% and with jet impingement with 59.43%. Kumar et al. experimentally investigated the performance and influence of artificial roughness multi-arc ribs and impinging jet solar air heaters, as illustrated in Fig. 10 [43]. The experiment achieved a thermo-hydrauclic of 4.1.

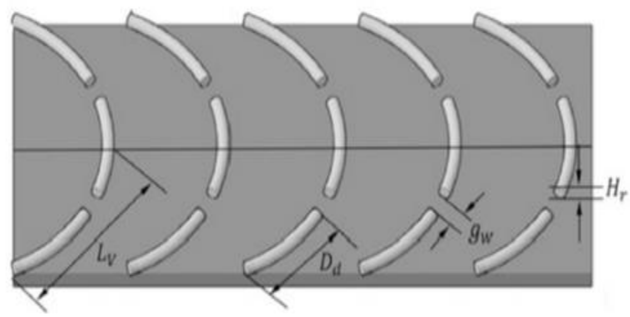

Fig. 10 Artificial roughness multi-arc ribs absorber plate [43].

Artificial roughness ribs are commonly attached to the absorber plate. The artificial roughness ribs jet impingement uses the same concept as the dimple surface jet impingement method. Air passes through the jet plate to produce impinging effects on the targeted surface. The difference between these two methods is the design of the surface. The dimpled surface uses a dimpled shapes design, whereas artificial roughness ribs are arranged to resemble ribs, using dimples shapes, straight lines, and V-shapes. Jet impingement with artificial roughness ribs is preferable to jet impingement with dimple surfaces. A dimple surface has less surface area than ribs arranged in rib forms. Artificial roughness ribs significantly improve the heat transfer as the laminar flow is breached through the ribs causing turbulent flow.

2.3. *Fins*

A study by Abhishek et al. evaluated a solar air heater's overall performance by combining jet impingement with fins [44]. Longitudinal arrangement fins are attached at the backside of the absorber plate, with a jet plate positioned underneath it, and the jet plate holes are drilled in a straight line. The experiment carried out three configurations: a solar collector without jet impingement and fins, a solar collector employing jet impingement only, and a solar collector employing the combination of jet impingement and fins, as demonstrated in Fig. 11. The result from the experiment achieved a maximum overall efficiency of 84%.

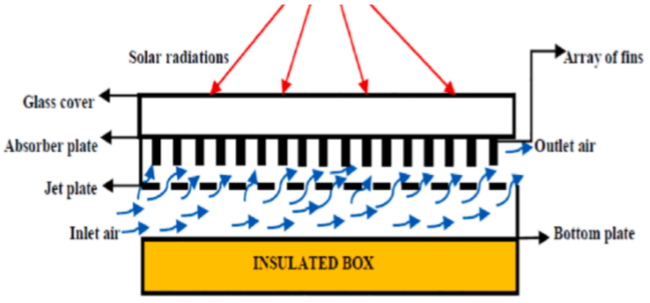

Fig. 11 Schematic view combination of jet impingement and fins solar collector [44].

Another study by Abhishek analyzes the heat transfer characteristics and essential geometrical parameters, including streamwise pitch ratio, jet diameter ratio, and fins spacing ratio [45]. The study was conducted through a Reynolds number of 5700-11,700 and air mass flow between 0.056kg/s to 0.112kg/s. Compared to simple flat-plate, the combination of jet impingement with fins significantly increases the heat transfer by 2.5 times.

The fins application is broadly used in many cooling methods. In addition, using fins as a heat sink is a proven method to cool down a surface. Fins are intended to increase the surface area. Heat will be applied to the fins with large and thin surface areas to ease heat dispersing. There are many studies on fins in solar applications, mainly in flat plate modules and double-pass solar collectors. However, fins application in the jet impingement method is still lacking. Further studies are suggested on combining fins and jet impingement to evaluate the potential of combining these two cooling methods.

2.3.1. *Conical Rings*

Alterations to the absorber surface shape, such as adding obstacles, can significantly impact the solar air heater's energy efficiency [46]. An effective way to enhance heat transfer is by applying conical rings within the air passage [47]. Conical rings improve heat transfer, resulting in a high-pressure drop [48]. The pressure drop in conical rings strongly correlates with the friction factor [49]. Nitin Kumar investigated the correlation of various conical ring obstacles inside a solar air collector to enhance heat transfer [50]. Fig. 12 illustrates the design of the conical ring in a jet impingement solar air heater. Uniform wall heat flux is applied to a turbulent flow at 5,000-23,000 Reynolds Number. Heat transfer is maximized at the X-axis and Y-axis with 5.28 and 3.42 pitch values, while the height of the conical rings is 0.110m, and the intake flow diameter is 1.7. The findings show that the Nusselt number significantly improves using a 0.110m conical ring height.

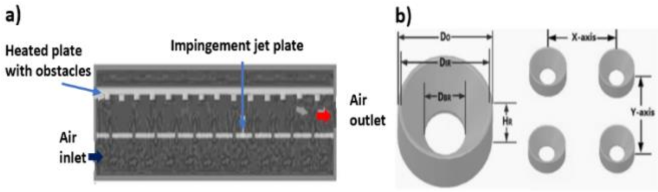

Fig. 12 Cross-section view of (a) solar collector with conical rings (b) Conical ring design [50].

The use of conical rings causes a swirling effect due to the air colliding with the conical rings. The swirling effect promotes turbulent flow, contributing to the heat transfer rate. The mixing between the fluid and solid domains prevents the development of boundary layers, significantly improving the heat transfer rate.

Based on the literature review on single-pass jet impingement, there are many studies performed on single-pass-double ducts. However, no studies have been found on the jet impingement method involving a single pass-single duct. The concept of a single-duct collector is not parallel to the existing jet impingement concept. Further studies are recommended to use a jet impingement concept in a single pass-single duct to make it possible to implement a jet impingement in a single pass-single duct solar collector. Compared to single ducts, a double duct solar collector with obstacles offers higher thermal and electrical performance. Artificial roughness ribs use the same concept of a dimpled surface. The artificial ribs and dimples are attached to an absorber plate, air is distributed through the jet plate to produce impinging effects on the surface target. Compared to these two methods, artificial roughness ribs significantly affect the solar collector performance more than dimple surface jet impingement.

The increased surface area of a corrugated plate makes it an efficient method of improving absorption and heat transfer. The actual length of a corrugate plate can be seen when it is straightened. Thus, the corrugated plate method in jet impingement is excellent for increasing the surface area while enhancing the heat transfer rate. Fins application in jet impingement methods also is preferable, as fins have been proven in many cooling methods. Combining both cooling methods increases the heat transfer rate 2.5 times. However, fins application with the jet impingement method is still lacking. More studies on combining these two cooling methods are needed to discover their potential for a solar collector performance.

3. Double Pass Jet Impingement

3.1. Double Pass-Double Duct

Recent research has shown that double-pass solar collectors operate thermally better than a single-pass solar collectors [51]. In addition, a double pass-solar collector outperforms a single pass-solar collector due to the absorber plate's high heat extraction rate and greater interaction caused by the doubled heat transfer surface [52], [53]. Double-pass solar collectors have 10-15% higher efficiency than single-pass collectors [54]. Essentially, air-to-absorber plate heat transfer must be improved to allow better solar collector performance while minimizing heat loss is maintained [55]. According to Sharol et al., increasing travel time results in a higher heat transfer rate, thereby decreasing thermal loss through the top cover [56]. Fig. 13 illustrate the fundamental of a double pass–double duct solar collector. Air enters the collector from two channels and the distributed along two different ducts. This subtopic reviews previous research on double duct jet impingement study and efficiency performance achieved.

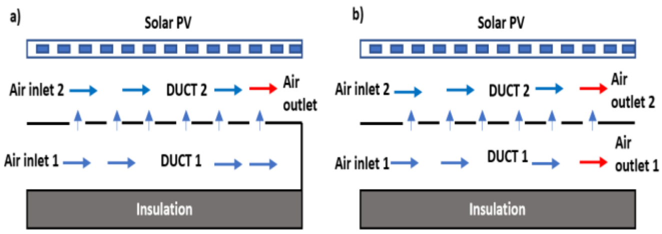

Fig. 13 (a) Double duct with one air outlet (b) Double duct with two air outlets.

A study by Nayak et al. investigated the flow characteristic across a staggering hole jet plate in a solar collector [57]. A total of 1173 jet holes were used in the experiment with two sets of mass flow rates, $\dot{m}_1$= 0.030-0.065kg/s and $\dot{m}_2$= 0.020-0.043kg/s, respectively, and a Reynolds number of 2700-6900. Air inlet $\dot{m}_1$ passes thru the jet plate holes and is mixed with $\dot{m}_2$ before exiting the top channel, as illustrated in Fig. 14. The study observed that the outlet temperature drops by about 3.2% while the collector efficiency increases to 3.6% at mass flow rate $\dot{m}_1$= 0.064kg/s.

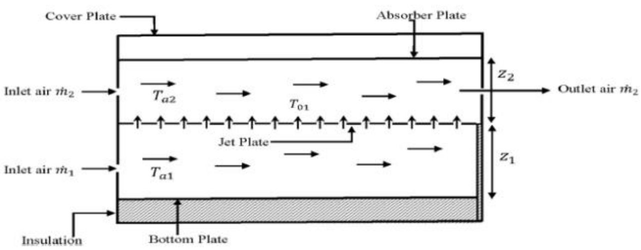

Fig. 14 Cross-section view of double pass- double duct solar collector [57] [58].

Another study using the same collector design investigated a jet plate's flow and heat transfer characteristics with streamwise ranges from 0.53-0.63m, spanwise ranges from 0.53-0.63m, and jet hole diameters varying from 0.053-0.084m [58]. The Reynolds number ranges from 4600-12,000. The study concluded that for all configurations of $\dot{m}_1$ and $\dot{m}_2$ improved the performance of solar collectors.

Satyender et al. investigate the performance of a solar collector by using a combination of wavy corrugated plates and circular jet holes on a double-pass solar collector, as illustrated in Fig. 15. [59]. An air-impinging jet with a diameter of 7.66mm was utilized on a perforated plate at a rate of 0.48%-1.4% through holes. The optimum thermal efficiency was achieved with a 0.04kg/s mass flow rate and 98% bed porosity. The highest thermal efficiency achieved was 94%, and thermo-hydraulic efficiency was 84%. In another study, a double pass-solar collector with jet impingement geometry and projecting absorber plate was subjected to a uniform heat flux of 1000W/m^2 and was experimentally analyzed, as presented in Fig. 16 [60]. The findings concluded that the efficiency of the jet impingement double pass-solar collector is conspicuously affected by the streamwise pitch ranging from 0.44-1.32mm and Reynolds Number of 2500-22,500.

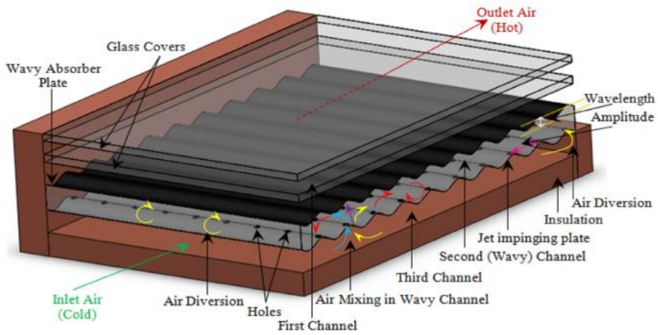

Fig. 15 Double pass jet impingement with corrugate wavy plate collector design [59].

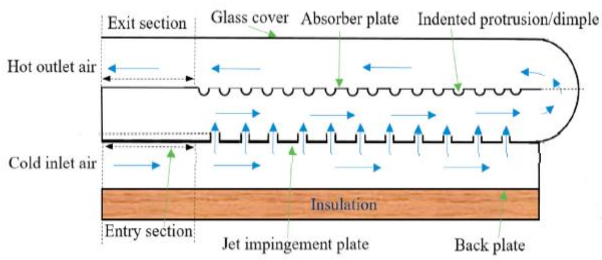

Fig. 16 Cross-section view of a jet impingement-dimple absorber plate in a double-pass solar air heater [60].

According to the literature review on double-pass jet impingement, previous studies have shown positive results in improving thermal performance. A study by Nayak et al. uses the solar collector design as presented in Fig. 14. The outlet temperature decreases by about 3.2% while the collector efficiency increases to 3.6% using a staggering jet plate with 1173 holes on a double-pass solar collector [57]. However, it was not stated that the actual collector efficiency value, the increase of 3.6%, remains unknown from the actual collector efficiency value. Based on the outlet temperature, it shows a slight decrease of 3.2%, which is from ±33ºC to ±32ºC only. Meanwhile, the collector design by Satyender et al. has a unique feature [59]. The solar collector combines three different cooling methods, which are double pass, jet impingement, and wavy corrugated plate in a solar collector. In previous literature, these three distinct cooling techniques have already demonstrated their potential to improve solar collector efficiency. The collector design achieved a remarkable thermal efficiency of 94%.

4. Concentrated PVT

4.1. Compound Parabolic Concentrator (CPC)

Essam M. et al. stated that triple junction solar cell is frequently employed in high concentrator photovoltaic (HCPV) configuration due to their high efficiency and favourable reaction to high concentration [61]. The author, in his study, examines the effects of the jet impingement method in maintaining a triple junction solar cell's optimal temperature. The findings demonstrated that the utilization of jet impingement methods resulted in an increase in both thermal and electrical energy generated. Essam M. et al., in another study, used the same concept and design with thermo-fluid on four different heat sink configurations with constrained jet impingement [62]. Fig. 17 illustrates the parabolic concentrator with a triple-junction solar cell using a jet impingement mechanism. Coolant fluid contributes to maintaining the solar cell temperature not exceeding more than 65°C. At a 25g/min flow rate, the exergy performance achieved its highest total exergy of 53%.

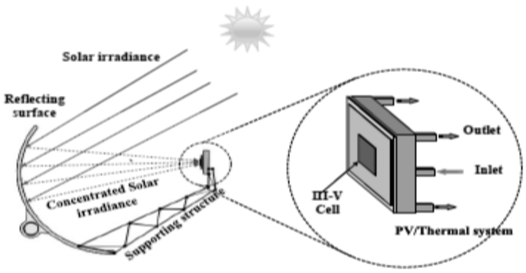

Fig. 17 Illustration of parabolic concentrator with a triple-junction solar cell using jet impingement cooling [61] [62].

A CFD design for a static water jet impingement on flat plate solar was developed by Francesco Anglani et al. to investigate the concentrated solar thermal flat reflector [63]. The impingement angle was set to 90˚, and shear stress contours with various inlet pressure and lengths were developed using ANSYS. The findings from the ANSYS simulation revealed that the nozzle design increases the impingement angle range of θ = 60˚-90˚. Fig. 18 illustrates the water jet nozzle.

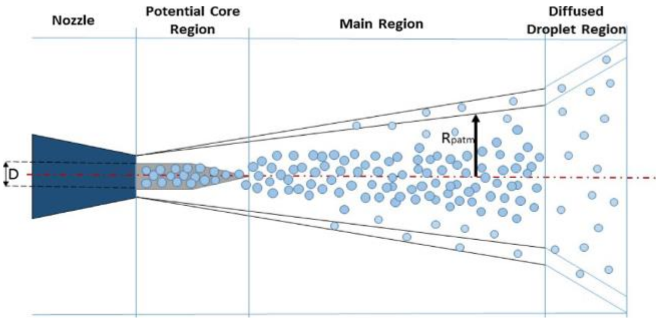

Fig. 18 Water jet nozzle characterization [63].

A study by Ahed Hameed et al. uses compound parabolic concentrator (CPC) and photovoltaic thermal. The CPC is cooled by an innovative fluid jet impingement method [64]. The experiment examines the impact of fluid jet impingement over the CPC solar collector, the total power generated, and the thermal and electrical efficiency. As presented in Fig. 19, the novel design achieved 7% of electrical efficiency, 81% of thermal efficiency and 31% improvement in the total output power.

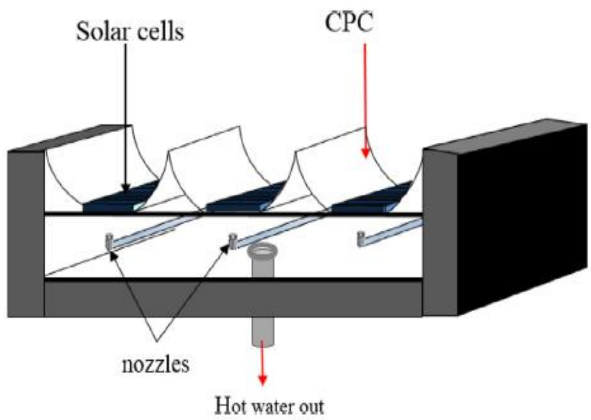

Fig. 19 CPC photovoltaic thermal jet impingement [64].

4.2. Microchannel

J. Barrau et al., in a study, stated that effective active cooling is needed in densely packed concentrated photovoltaic (CPV) to regulate and preserve the photovoltaic cell's optimum operating temperature [65]. The study carried out an outdoor experiment focused on concentrating photovoltaics using a microchannel-impinging jet mechanism to regulate the temperature. According to the result of the study, the cooling device temperature uniformity and thermal resistance coefficient exceeded the criteria for the CPV receiver. Another study by M. Awad et al. designed a unique impinging jet microchannel heat sink with an integrated heat spreader to evaluate the performance of a CPV system [66]. Fig. 20 depicts the CPVT system with jet impingement microchannel heat sink and heat spreader. The study concluded that integrating the techniques proposed in the CPV system increases the electrical efficiency and net power.

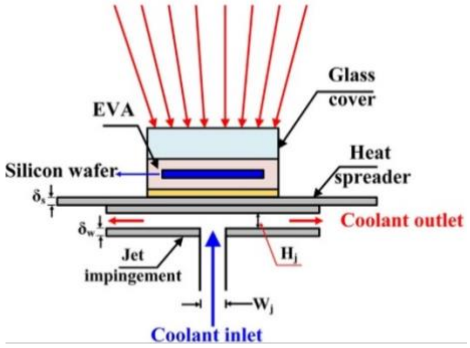

Fig. 20 Schematic diagram of CPV with a combination of jet impingement microchannel heat sink and heat spreader [66].

Hosny et al. developed an effective microchannel system for a high-concentration multi-junction photovoltaic cell (HCMJPV). The system utilizes the concept of a short cooling fluid path with one or two microchannel paths [67]. The thermal properties of the microchannel and the power generated by the proposed design are examined. According to the findings, the microchannel design results in a lower surface temperature and pressure drop to 68.41%, along with an output power increase to 8.44%. A novel heat dissipater jet impingement microchannel was introduced by Essam M. et al. [68]. The design consists of rows of rectangular fins along the heat sink. Fig. 21 shows the high concentrator photovoltaic thermal system (HCPVT) with a microchannel cooling device. The overall exergy efficiency of the hybrid system was 53.5% at a 25g/min inlet mass flow rate, and the electrical efficiency increased to 39.7%.

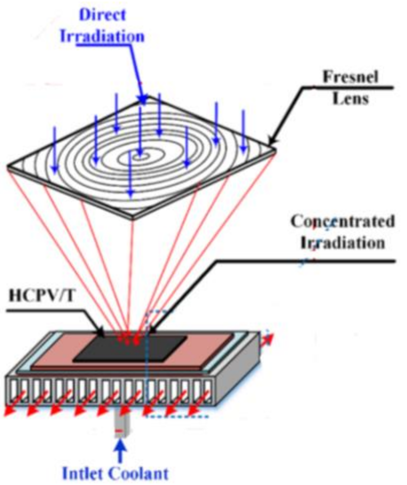

Fig. 21 HCPVT configuration design with hybrid jet impingement microchannel heat sink [68].

A jet impingement microchannel heat dissipator model was proposed to reduce the surface temperature of the triple junction concentration solar cell, as illustrated in Fig. 22. Torbatinezhad et al. numerically analyzed a concentrated solar photovoltaic system with a jet impingement microchannel heat sink [69]. The influence of pin fin angle on the system was investigated for various concentration ratios and flow rates. In terms of heat dissipator fin orientation, as the angle of the fin increase from θ = 0˚- 40˚, the heat sink temperature decreases from 321.9K to 321.2 K. When the mass flow rate reaches 150g/s, the electrical efficiency achieves a 29% increment while the thermal efficiency increases by about 80%. CFD simulation was used to simulate and analyze a high-concentration multijunction photovoltaic cell by employing a microchannel-hybrid cooling system with jet impingement [70]. The simulation was conducted with different operational settings, and the inlet temperature varies from 10-80˚C, the mass flow rate ranges from 16-20mL/s, and the heat flux ranges from 10-90W/cm^2. According to the results, the output power is proportional to the input heat flux.

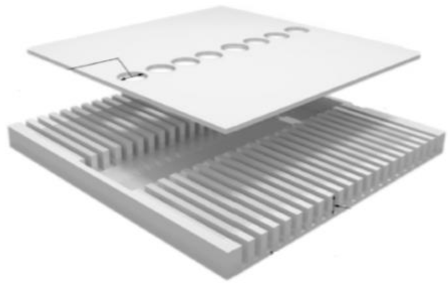

Fig. 22 Schematic diagram of the microchannel with jet impingement inlet [69].

Many studies on concentrated PVT with jet impingement are mainly characterized as compound parabolic concentrator (CPC) and microchannel. Compound parabolic concentrator (CPC) and jet impingement aim to improve a solar module's performance. However, these two methods work in different manners. The CPC increases the electrical performance of a solar module by concentrating more sunlight using a highly reflecting surface. The angle of the parabolic concentrator and its reflecting surface plays a vital role in increasing a solar module's electrical performance. Concentrating more sunlight to be absorbed by the solar cell will also result in more heat gain by the solar cell. Where else, the function of a jet impingement is to cool down a solar module temperature to recover the performance loss due to the heat gain.

Combining a CPC and jet impingement in a solar collector can balance the heat gained from absorbing the sunlight and regulating the solar module temperature. Combining these two methods in a solar collector can improve the electrical and thermal performance of the collector. This was proven by the previous study, which achieved a 7% increase in electrical efficiency, an 81% increase in thermal efficiency, and a 31% increase in total output power using the design proposed in Fig. 17 [64]. Meanwhile, a microchannel jet impingement more or less serves the same functions as a CPC jet impingement. A microchannel jet impingement study, illustrated in Fig. 22, achieved a 29% increment in electrical efficiency and 80% in thermal efficiency [69]. Meanwhile, an overall exergy efficiency of 53.5% and a maximum electrical efficiency of 39.7% using the design presented in Fig. 21 [68]. From the literature review, it can be concluded that microchannel performs way better in electrical efficiency than CPC.

5. Jet Impingement Configuration

Jet impingement technique, either jet plate or jet nozzle, has been the main subject of previous research to improve or modulate heat transmission that will be elaborated on in this subtopic. PV panel temperature can be controlled and maintained uniformly using jet impingement, which also helps increase PV efficiency [71]. The nozzle streamwise and spanwise pitch, nozzle to target spacing, nozzle diameter, nozzle shape, and Reynold Number significantly impact the heat transmission properties of the jet impingement array [72]. Rows or arrays of numerous jets are used for large heat transfer surfaces [73]. Numerous jets are required to attain a degree of homogeneity temperature that is adequate [74].

5.1. Jet Plate

A study by Matheswaran et al. developed and analyzed a Single Pass-Double Duct Jet Plate Solar collector with flow rate, ṁ ranging between 2 to 23g/s [75]. Fig. 23 shows the cross-section view of the collector design. The results show that the performance efficiency increases by about 21%, and the exergy increases about 22.4%. ANSYS CFD simulation model was used to analyze the heat transmission properties of an impinging jet solar air heater combined with an absorber plate [76]. The Reynolds Number spans from 3,500 to 17,000, and jet diameter ranges between 0.065m and 0.433m, respectively. According to the findings, jet diameter ratio of 0.0650 and Reynolds value of 17,5000 achieves the highest heat transmission of 7.58.

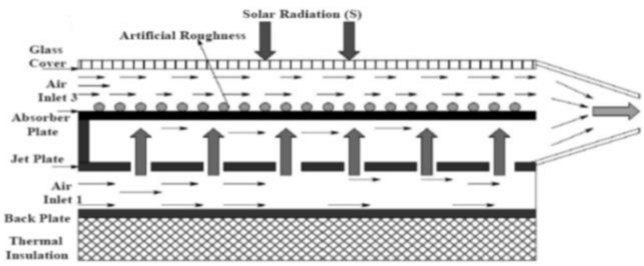

Fig. 23 Single Pass-Double Duct Jet Plate Solar Collector design [75].

Rachan et al. experimented with examining the effect of heat transmission and fluid friction on geometrical modifications of jet impingement [77]. The Taguchi-based design method was used to optimize parameters for efficient energy conversion. The study observed that the streamwise and spanwise contributes to the improved efficiency of 37-48.3% at Reynolds number 4000-16,000. Another study by Rachan et al. uses the jet impingement technique on a solar collector to study the friction factor and heat transmission properties [78]. The streamwise, spanwise and jet diameters range is 0.109-0.435m, 0.435-0.866m, and 0.043-1.73m. Fig. 24 illustrates the geometry of streamwise pitch and spanwise pitch. The result observes that the friction factor increases by 3.5 and heat transfer by 2.67, respectively. Both streamwise and spanwise variations in jet pitch significantly affect the efficiency of a jet impingement solar collector [79].

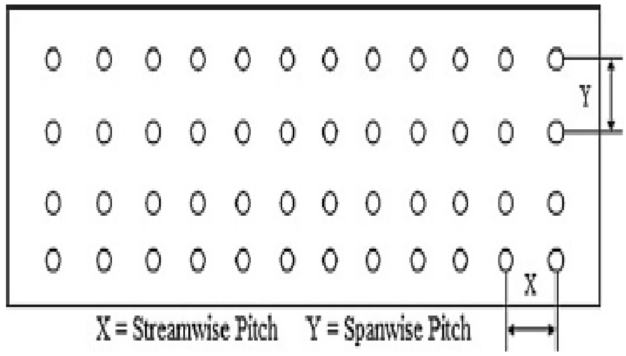

Fig. 24 Streamwise and spanwise pitch geometry[78], [79].

An analysis was conducted to evaluate the performance and criteria for determining the optimum design of a jet impingement solar collector [80]. As stated by the study, jet impingement improves thermal performance while increasing friction power. The position of streamwise and spanwise on the jet plate is shown in Fig. 24, and the solar collector design is demonstrated in Fig. 25. As a conclusion from the study, the optimal parameter configuration is as follows: 0.435mm streamwise ratios, 0.869mm spanwise ratios, 0.065mm jet diameter, and Reynolds number 16,000.

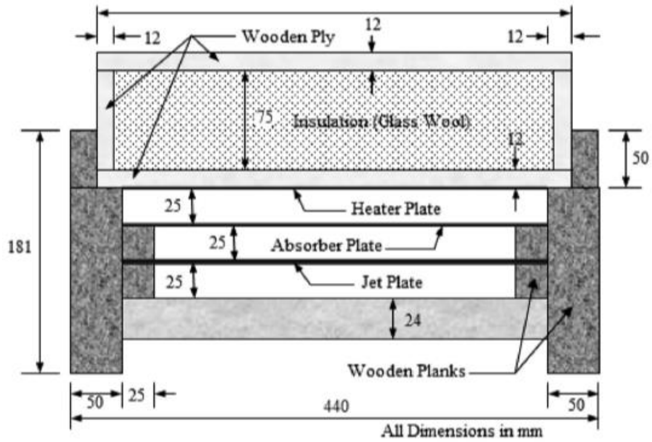

Fig. 25 Schematic solar collector jet impingement diagram using jet plate [80].

Heat transfer in a bifacial photovoltaic thermal (BiPVT) solar collector with a jet plate was examined using a novel energy balance equation by Eng Ewe et al. [81]. With the configuration of 0.66 packing factor, 0.035kg/s mass flow rate, and 900W/m^2 solar irradiance, the maximum thermal efficiency achieved was 51.09% and electrical efficiency 10.69%. Another study by Eng Ewe investigates a bifacial PVT jet impingement thermo-electro hydraulic performance [82]. Dual function jet plate reflector with 36 holes was proposed to increase light absorption of the bifacial PV cell, as shown in Fig. 26. The packing factor of the bifacial cell was varied. The bifacial jet impingement PVT achieved a thermal of 57.3%, electro efficiency of 10.36%, and thermo-electrohydraulic of 83.93%.

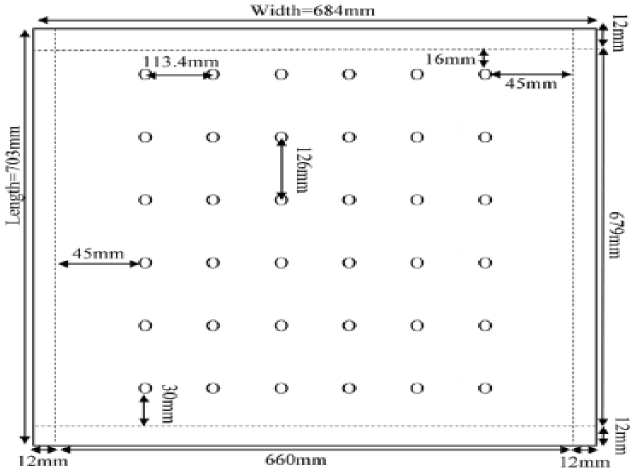

Fig. 26 Jet plate reflector streamwise pitch, X= 126 mm, and spanwise pitch, Y= 113.4 mm [81], [82].

5.2. Jet Impingement Configuration

Jet impingement using a jet nozzle uses an array of nozzles to distribute air or water as the working fluid. A study by Husam et al. developed a jet impingement PVT using nanoparticles as the cooling media [83]. By using the nanoparticles, the thermal efficiency achieved was 85%, and the electrical efficiency was 12.75% under solar irradiance of 1000W/m^2. Another study, on the other hand, proposed a mechanical approach of water jet system installed above the PV module to eliminate dust and reduce the temperature of the PV module [84]. The proposed design showed an increment in the output power by 27%.

Javidan et al. conducted an experimental research on the nozzle configuration in a jet impingement collector (diameter size, nozzle spacing, nozzle numbers) [85]. The design of the experiment is illustrated in Fig. 27. The output power achieved was 47.67% in an optimum condition of max 24 number of nozzle, 1mm diameter, and 5mm nozzle-to-target spacing.

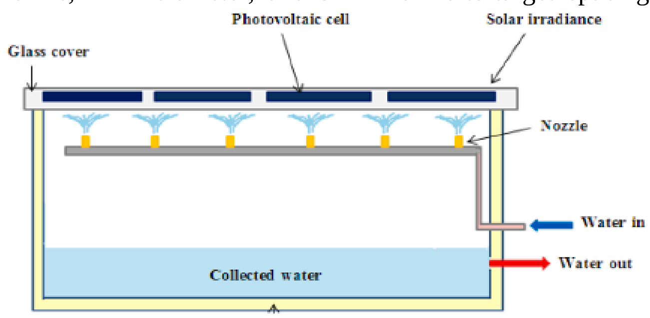

Fig. 27 Jet impingement using nozzle configuration [85].

In a study, analyze the heat transfer of a solar cell temperature with a single nozzle jet impingement as shown in Fig. 28 [86]. The result shows that the electricity output and conversion efficiency improve by 82.6% and 49.6%, respectively. Meanwhile, a study by Husam et al. conducted an experimental study on a water jet collision PVT with solar irradiance ranging from 500-1000W/m^2 with a mass flow rate ranging from 3.3-60g/s [87]. The findings of the experiment achieved 81% thermal efficiency at 1000W/m^2 solar irradiance.

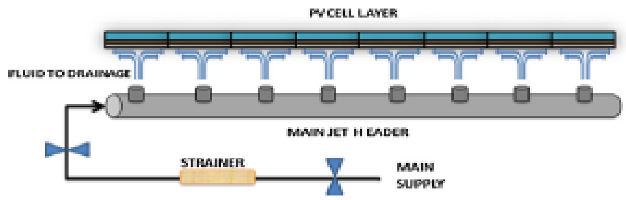

Fig. 28 Single nozzle jet impingement solar cell [86].

Rajesh et al. form a jet impingement from pipes attached to a branch configuration to allow air to be distributed at an incline angle [88]. The proposed design achieved 2.39 thermo-hydraulic performance at mass flow rate of 0.054kg/s and streamwise of 0.285m. Fig. 29 presents the jet impingement configuration of the experiment. İn another study, air is distributed through a pipe with a jet impingement nozzle to transfer and remove heat throughout the solar collector [89]. The results achieved an efficiency of 55% at 0.016kg/s mass flow rate.

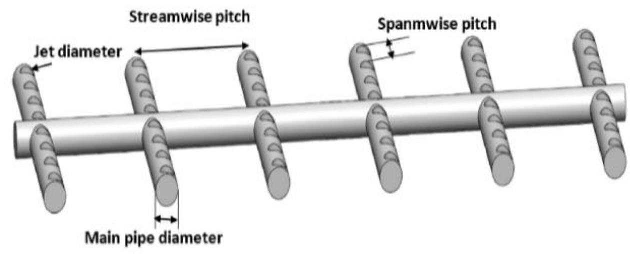

Fig. 29 Pipes configuration acting as jet impingement [88].

The jet impingement technique using a jet nozzle or jet plate has been the main focus of prior studies to improve or regulate heat transfer in a solar application. Much of the research done using jet impingement has produced an outstanding results in improving a solar collector's heat transfer and performance. The streamwise and spanwise of the jet plays a vital role in achieving optimum results. Using jet plates has proven to improve solar collector efficiency significantly. A 21% increase in the efficiency performance and a 22.4% increase in the exergy efficiency were achieved using the solar collector design in Fig. 23 [75]. Another study using the jet plate, as shown in Fig. 26, achieved a thermal, electrical, and overall efficiency of 51.09%, 10.69%, and 61.78%, respectively [81].

Based on the literature, jet nozzle configuration results in higher efficiency than jet plate configuration. In addition, a jet nozzle with water as the working fluid tends to have higher efficiency than air. A jet nozzle using impinging nanoparticles fluid (SiC, TiO2, and SiO2) on a PV module at solar irradiance of 1000W/m^2 achieved a thermal efficiency of 85% and electrical efficiency of 12.75% [83]. A water-based jet nozzle can achieve more than 80% efficiency compared to an air-based, which can only achieve a 50-80% efficiency increment.

6. Conclusion

The jet impingement cooling technique is broadly used to improve the efficiency of solar energy technologies. Numerous researches have been conducted to enhance the efficiency of the solar collector using jet impingement. This paper comprehensively presents the design and performance of jet impingement mechanism on solar collector, photovoltaic and photovoltaic thermal. The review has been classified into four main components: single-pass collector, double-pass collector, concentrated collector, and jet configuration, as shown in Fig. 1. Each section discusses and elaborates on studies on implementing jet impingement mechanisms based on the design and performance achieved.

Based on the literature review, no research on the jet impingement approach utilizing a single pass-single duct is available. Hence, further studies are recommended to make use of a jet impingement concept in a single pass-single duct solar collector possible. It can also be concluded that improving the electrical and thermal performance of the collector can be achieved through the combination of compound parabolic concentrator (CPC) and jet impingement method.

On the other hand, microchannel jet impingement offers remarkable results in terms of electrical efficiency compared to CPC jet impingement when it comes to concentrated PVT jet impingement classifications. Meanwhile, for the jet configuration classifications, the efficiency achieved by jet nozzle configurations is significantly higher when compared to jet plate arrangements. The efficiency of jet nozzles utilizing water-based as working fluid is often higher as opposed to air-based working fluid. Table 1 summaries the efficiency performance of reviewed jet impingement methods applied in solar applications discussed in this paper.

Table 1 Summary of previous study efficiency performance

Ref	Year	Method	Implemented Approach	Efficiency (%)
[24]	2021	Theor	Performed exergy and cost analysis on dimple roughened solar collector.	η_{exe} = 2.6%
[30]	2017	Exp	Analyzed performance of jet impingement solar collector with corrugated plate.	η_{th} = +14%
[31], [32]	2018, 2016	Exp	Developed a glazed transpired solar air collector with corrugated plate.	η_{th} = 60%
[41]	2021	Theor	Analyzed the effects of transverse rib imprinted on an absorber plate jet impingement solar collector.	η_{th} = 78%
[42]	2021	Theor	Performed exergy, energy and economic study to optimize a rib roughness solar collector.	η_{PVT} = 58.81%
[44]	2022	Theor	Evaluate the performance of solar air heater with jet impingement and fins attached to the absorber plate.	η_{PVT} = 84%
[57]	2020	Exp	Investigate flow characteristics of a staggered hole jet impingement solar collector.	η_{PVT} = +3.6%
[59]	2020	Exp	Analyzed the performance of a wavy corrugated plate's jet impingement.	η_{th} = 94%
[62]	2018	Theor	Investigate the exergy performance of four different heat sink jet impingements.	η_{exe} = 53%.
[64]	2018	Exp	Analyze a CPC PVT with jet impingement.	η_{elec} = 7% η_{th} = 81%
[67]	2020	Theor	Developed a high-concentration multi-junction photovoltaic cell.	η_{elec} = 8.44%
[61]	2020	Theor	Introduced a novel heat dissipater jet impingement microchannel.	η_{PVT} = 53.5% η_{elec} = 39.7%
[75]	2018	Theor	Analyzed a single pass-double duct jet plate solar collector.	η_{PVT} = +21% η_{exe} = +22.4%
[77]	2017	Theor	Examine effect of heat transmission and fluid friction of a jet impingement.	η_{PVT} = +48.3%
[81], [82]	2022, 2021	Theor	Analyzed the performance of a bifacial PVT jet impingement	η_{th} = 57.3% η_{elec} = 10.36%
[83]	2017	Exp	Analyzed the performance of PVT solar collectors with nanoparticles.	η_{th} = 85% η_{elec} = 12.75%
[84]	2019	Exp	Proposed a water jet system above the PV module.	η_{elec} = 27%

[85]	2021	Exp	Investigate the nozzle configuration in a jet impingement collector.	η_{elec} = 47.67%
[86]	2016	Exp	Analyzed heat transfer for a single nozzle jet impingement solar cell.	η_{elec} = 82.6%
[87]	2018	Exp	Experimental on a water jet collision PVT.	η_{elec} = 81%
[89]	2017	Exp	Experimental a jet impingement to remove heat in a solar collector.	η_{PVT} = 55%

The design and performance of the jet impingement cooling methods in solar collector application was discussed in this paper. A summary of relevant formula involving the performance of jet impingement methods is summaries as Table 2.

Table 2. Relevent formula of jet impingement performance analysis.

Ref	Variables	Formula
[81]	Energy Performance	$\eta_{elec} = \frac{Pmax}{I \times Ac}$ $\eta_{th} = \frac{\dot{m}C_p(T_{out}-T_{in})}{I \times Ac}$ $\eta_{PVT} = \eta_{elec} + \eta_{th}$
[85]	Exergy Performance	$\eta_{exe} \frac{exe_{output}}{exe_{input}}$
[82]	Thermo-hydraulic	$\eta thermo = \frac{P_{max}-P_{fan}}{I \times Ac}$ Where P_{fan} *is given* by: $P_{fan} = \frac{P_m}{\eta_{fan} \times \eta_{motor} \times \eta_{transmission}}$
[62]	Nusselt Number, Nu	$Nu = 0.0293(Re)^{0.8}$ Where *Re* is the Reynolds number
[80]	Friction factor	$Re < 2250, f = \frac{24}{Re} + 0.9\frac{H}{L}$ $2250 < Re10^4, f = 0.0094 + 2.92Re^{-0.15}\frac{H}{L}$ $10^4 < Re10^5, f = 0.059Re^{-0.2} + 0.73\frac{H}{L}$
[41]	Output power	Heat gain, $Qu = \dot{m}C_p(T_{out} - T_{in})$ For electrical output, $\eta_{cell}G\alpha A$

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