International Journal of Fisheries and Aquatic Studies 2018; 6(5): 342-347

E-ISSN: 2347-5129
P-ISSN: 2394-0506
(ICV-Poland) Impact Value: 5.62
(GIF) Impact Factor: 0.549
IJFAS 2018; 6(5): 342-347

www.fisheriesjournal.com
Received: 04-07-2018
Accepted: 08-08-2018

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Surface aeration systems for application in aquaculture: A review

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Abstract
Surface aeration systems viz., paddle wheel and spiral aerators are the most commonly used aeration systems in intensive aquaculture practices. Use of aerators in intensive aquaculture is important for ensuring better survival, optimal oxygen supply, higher production, and disease free environment. Hence, selection of properly designed and high efficient aerators is necessary to maintain adequate and continuous supply of dissolve oxygen (DO) in semi-intensive and intensive aquaculture and keep the energy consumption (operating cost) to minimum. Paddle wheel and spiral aeration systems have advantage of cost effectiveness, low maintenance and easy availability. In the present study a review on previous studies related to standard aeration efficiency (SAE) and standard oxygen transfer rate (SOTR) of paddle wheel and spiral aeration systems has been discussed.

Keywords: aerators, dissolved oxygen, standard aeration efficiency, standard oxygen transfer rate

Introduction
In intensive aquaculture system increased fertilization, excessive feeding and high stocking density the natural aeration is insufficient and will be a limiting factor for production. Therefore, artificial aeration is very much essential for survival of intensively cultured aquatic flora and fauna. It is estimated that additional 500 kg of fish production can be achieved per kW of aeration (Boyd, 1992) [13]. Aeration cost is the third largest cost in intensive aquaculture system after post larvae and feed cost representing about 15% of total production cost (Kumar *et al*., 2013) [11]. Aerators contributes significant amount in the total production cost in intensive aquaculture. However, good aquaculture water quality ensures healthy and faster growth of culture species. Therefore, aquaculture water quality is an essential parameter to be considered in intensive as well as semi-intensive aquaculture systems. Mechanical Aeration enhances water quality and also improves the aqua-cultural yield. It also reduces the settlement of feed at the bottom of the pond. Dissolved oxygen (DO) is one of the most important water quality parameters affecting the quality of aquaculture water. Oxygen enters into the water body by absorption from the atmosphere or by plant photosynthesis. It is removed by respiration of organisms and decomposition of organic matter. The DO level of culture environment has direct influences on spices growth fertility, survival rate, feed intake and digestion Drop in the DO level below the critical level can induce stress for aquacultural species. The growth of algae and bacteria also consume oxygen which also results in the reduction of DO level. The purpose of artificial aeration is to maintain the amount of oxygen level (DO) in aquaculture system within the permissible limit (6-8 mg/L) (Reference??). Aeration will also destroy the formation of any vertical temperature, salinity and chemical stratification by proper circulation and mixing of the pond water.

Aeration process
Transfer of oxygen into a water body can be simplified as a three step process.
1. Transfer of oxygen in the gas to gas liquid interface.
2. Transfer across the gas liquid interface.
3. Transfer of oxygen away from the interface into the liquid.

The first step is accomplished by a combination of diffusion and convective currents in the gas and is a relatively rapid process. The second step consists of diffusion only and is a relatively

Slow process. It is the rate which limits the transfer process.
The rate at which a slightly soluble gas such as oxygen is transferred into a liquid is proportional to the area of gas liquid interface and the gradient between the existing and saturation concentration of gas and liquid, the magnitude of liquid film coefficient and the turbulence.

Surface aerators

Surface aerators are used to break up or agitate the surface of water bubbles so that oxygen transfer takes place. For eg. i) Pump spraying water into air, ii) water pumped through nozzles and iii) hydraulic jump. Surface aeration systems used mainly in pond aquaculture systems are: i) paddle wheel aerator and ii) spiral aerator.
The most important parameters for evaluating the performances of the surface aerators are standard oxygen transfer rate (SOTR) and standard aeration efficiency (SAE).SOTR define the amount of oxygen transfer into the water body per unit time and SAE is the ratio of SOTR to power consumption of shaft. The SOTR is a function of oxygen transfer coefficient (K_La) and SAE is a function of SOTR and power requirement to run the aerator to transfer enough amount of oxygen from the atmospheric air to water.
The standard oxygen transfer rate (SOTR) can be expressed as follows

$$SOTR = (K_L\,a)_{20} * V * \Delta C \quad \text{... (1)}$$

Where,
SOTR = Standard Oxygen Transfer Rate (kg of O_2/h),
$(K_L\,a)_{20}$= Oxygen transfer coefficient at 20° C (h^{-1}),
ΔC = C^*_{20-0} = saturation DO concentration at 20°C
V = volume of water under aeration, m^3.
The standard aeration efficiency (SAE) can be expressed as follows

$$SAE = SOTR / P \quad \text{... (2)}$$

Where,
SAE = Standard Aeration Efficiency (kg O_2 / KW-h)
P = power required to run the aerator (KW)

Paddle wheel aerator

A paddle wheel aerator is a common example of surface aerator. Aeration is done on the pond or by constant splashing of air into the atmosphere by this type of aeration system. The paddle wheel aerator has the following parts: An electric motor – 1 No., a reduction gear box or a reducer – 1 No., connecting shaft – 2 Nos., base frame – 1 No., anchor or aerator setting bar – 4 Nos., movable joints; engine cover – 1 No., floats and rotating wheel or impeller (number of floats and impeller depends on SOTR and SAE) (Fig. 1).

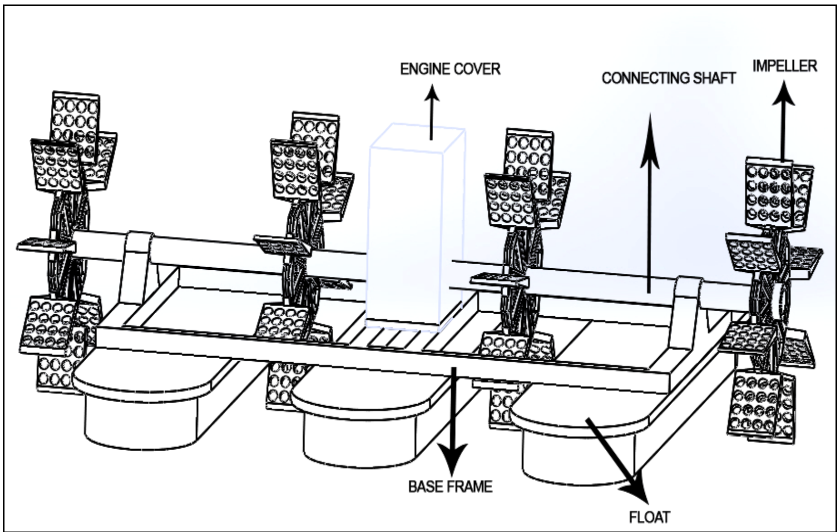

Fig 1: Parts of Paddle wheel aerator

Function

Due to continuous rotation of wheel, pond water is splashed or splited its open air. The spilled water particles contact with air present in atmosphere and return back to surface of water. Constant rotation of wheel imports oxygen in the pond. The continuous circulation goes accumulated at the bottom splashing of water at surface gives temperature at control i.e. thermal stratification is destroyed. Excess O_2 is sent out by splashing and super saturation maintained. Thus, DO content is maintained and kept under control.
The SOTR depends on the intensity of turbulence which in turn depends on the following factors such as [3]

1. Speed of the rotor
2. Paddle immersion depth
3. Length of the paddle
4. Paddle wheel diameter
5. Number of paddles
6. Total length of the aerator
7. Shape and size of the aeration tank/pond
8. Biological, chemical, mineral (salinity) content of the water
9. Number of bubbles created per unit volume, size of bubbles & distribution of bubbles in the water.

Paddle wheel aeration in aquaculture water treatment

Boyd *et al*. (1988) [1] studied the performance of paddle wheel aerators having plastic pipe (PVC) paddles. It was reported that values of standard oxygen transfer rate (SOTR) and standard aeration efficiency (SAE) for paddle wheel aerator with PVC pipe paddles were lower than those with steel paddles. Their study also revealed that the average SOTR value for steel paddle aerator was 20.2 kg O_2 h^{-1} whereas for PVC paddle aerator it was 2.17 kg O_2 h^{-1}. Hence, it can be suggested that by increasing the number of PVC paddles on the aerator, enhance both SOTR and SAE of the PVC paddle wheel aerator significantly. The non corrosive nature and low cost of PVC pipes making it a suitable material to be used in the aeration system.

Fast *et al*. (1999) [9] observed that the presence of salt in the water (salinity) affects the oxygen transfer efficiencies significantly for the paddle wheel aerators. The Oxygen transfer rates or standard aeration efficiencies (SAE) were increased with increase in the salinity of the water. The increase in SAE of saline water was observed due to creation of large number of bubbles (even-though size of bubble is small) in saline water when compared to fresh water. The reason for more number of bubbles was due to difference in the surface tension between fresh and saline water. From the study, the reviewers suggested that shrimp / fish culture could be done in water containing significant percentage of salt rather than fresh water due to increase in SAE of the saline water. Therefore, it increases productivity which in turn benefits the farmers economically.

Moulick *et al*. (2002) [14] developed simulation equations using non dimensional analysis to predict the values for performance parameters like SAE, effective power, SOTR for different geometrical and dynamic values of paddle wheel aerator. Their study also evaluated the scaling effects on non dimensional number such as SAE and power number (N_e) using Reynolds and Froude numbers. The authors suggested that simulated correlations of paddle wheel aerators will be helpful for obtaining optimum value for geometric and dynamic parameters to run them efficiently. These equations also reduce the development and testing cost of paddle wheel aerators.

Delgado *et al*. (2003) [8] studied the effect of chemical, physical and biological characteristics on shrimp life at different regions (within pond) in paddle aerated shrimp pond. Their study reported that pond outer region was well mixed and aerated (high DO) whereas in inner region (in the centre), DO was found to be low due to high accumulation of organic and sludge accumulations (vertical stratification formed at the centre) at the bottom of the inner region. Hence, shrimps were found in abundance at the outer region rather than at inner region (not suitable condition for growth at the inner region). The authors suggested that regular flushing of sludge from the inner region need to be done in paddle aerated aquacultural ponds.

Moulick *et al*. (2005) [15] studied the effect of volume of water on oxygen transfer rate at various dynamic conditions of single hub paddle wheel aerator. They also developed simulated equations to arrive at an optimized value for parameters viz., volume of water, non-dimensional numbers (power number (N_e), power input per unit volume (p^*)) at various dynamic conditions to achieve maximum aeration efficiency (SAE). A simple correlation to determine the optimum value for paddle wheel speed and paddle wheel diameter to achieve required amount of SOTR was also presented. The authors observed that increasing the paddle speed and diameter increases SOTR. However, it also increases the power requirement which in turn reduces the SAE. Therefore, optimum paddle wheel diameter and speed have to be considered in designing paddle wheel aerators to achieve better SOTR without comprising SAE.

Romaire and Merry (2007) [19] studied the effects of plantation of rice *Oryza sativa* in the aquatic cultural ponds culturing red swamp crawfish with and without paddle wheel aerators. It was reported that there was no difference in the crawfish yield between the ponds aerated with paddle wheel aerators and the ponds without aerators. The use of paddle wheel aerators only reduces the frequency of flushing and occurrence of hypoxia in the ponds when compared to those with non-aerated ponds, but it didn't show any significant rise in the crawfish yield when cultured in the mono-cropped (planted with rice) land. It was observed that the rice vegetation acted as forage for the crawfish which reduces the oxygen demand. The authors suggested that the same plantations method may be tried for different aqua-spices and its yield may be calculated with and without the use of paddle wheel aerators. Moreover, the efficiency of paddle wheel aerators in the mono-cropped or double cropped cultured land may also be studied.

Taparhudee *et al*. (2007) [22] carried out a comparative study between electric motor operated paddle wheel aerators and diesel engines operated paddle wheel aerators in terms of parameters viz., water velocity, water quality, chemical content, biological content, soil quality, production, profit and energy cost in pacific white shrimp culture ponds. In diesel powered paddle wheel aerator, all the above parameters were found to be marginally high and it also had higher shrimp growth rate due to lower survival rate. It was inferred that water velocity was found to be high in diesel engine powered paddle wheel aerator which could enhance dissolved oxygen, provides better mixing, flushing of the pond by moving the waste towards the centre of the pond. The authors suggested that even though the profit was found to be slightly higher in diesel engine aerators, the electrically powered aerators could be advantageous in terms of low maintenance cost, longer life, less noise. It is in the hands of the farmers to choose the aerator wisely according to their requirements. Further, the non-conventional energy (like solar energy) powered paddle wheel aerators may be developed and its performance and cost effectiveness may also be studied.

Moulick and Mal (2009) [16] studied about performance of double-hub paddle wheel aerator to determine optimized value for paddle wheel diameter, speed and non-dimensional number (N_e & P^*) at various dynamic conditions to achieve required SOTR and maximum aeration efficiency (SAE) respectively. By comparing this study with the performance of single-hub paddle wheel aerator (Moulick *et al*., 2005) [15], it was found that there was no deviations in SAE due to increase in the power consumption of the double hub paddle wheel aerator. The value SOTR was high in double hub when compared to single hub paddle wheel aerators. The authors observed that increasing the number of hubs increases SOTR. But, it won't improve SAE as power consumption is increased with increasing number of hubs. It is also inferred that number of hubs is choosed based on the size of the pond to be aerated.

Evaluated the effect of blade configurations, rotational speeds, filling level on power consumptions, paddle wheel efficiency and fluid velocity (U_c) of the paddle wheel aerators in an open raceway pond. Their study used four different blade configurations (zigzagged, flat, forward curved & backward curved). It was reported that the paddle wheel with zigzagged blade produced larger fluid velocity at lower cultural depth whereas flat blade led to larger fluid velocity at higher cultural depth. The power consumption was highest for zigzagged blade and least for backward curved blade. The flat blade showed highest efficiency whereas backward curved blade achieved lowest efficiency. The authors inferred that the blade configurations which led to larger surface area interactions with the fluid increase the fluid velocity due to higher turbulence intensity. However, it increases power consumption. It is suggested that while designing different blade configurations, a balance between increasing fluid velocity and cost of power consumption to be considered in order to achieve maximum aeration efficiency.

Kumar *et al*. (2013) [11] carried out a comparative study about four types of aerator systems (circular stepped cascade (CSC), pooled circular stepped cascade (PCSC), paddle wheel and propeller aspirator pump) in terms of standard aeration efficiency (SAE) to select suitable aerators according to the user requirements for intensive aqua-cultural ponds. It was reported that paddle wheel aerator was suitable for larger sized pond (>5000 m^3) and also for maintaining better water quality. The CSC and PCSC were economical for pond size less than 1000 m^3. The reviewers observed that size of the pond is one of the parameters for determining the aeration cost. As the aeration cost contribute around 15% to the total production cost, an economical selection of aeration system may improve the profit of the aquacultural unit.

Roy *et al*. (2015) [20] conducted experiments to determine the effect of different rotational speeds of paddle wheel aerators on SOTR, SAE and aeration cost. They also developed simulation equations for power consumption and oxygen transfer. It was reported that maximum SAE was found at a rotational speed of 160 rpm for pond volume of 24m^3. But, the least aeration cost was achieved at lower rpm (80 rpm) for smaller pond volume (<700 m^3). The authors suggested that increasing rotational speed increase SOTR as well as power consumption which in turn increases aeration cost or vice-versa. Increasing the rotational speed increases SAE first and decreases after certain speed (optimum speed – speed at which SAE becomes maximum) because power consumption becomes more compared to oxygen transfer rate. Hence, running the paddle wheel aerator at an optimum rotational speed (differs based on the pond size) may reduce the aeration cost which benefits the farmer economically. Optimum rotational speed increases with size of the pond.

Bahri *et al*. (2015) [2, 3] simulated the effect of blade geometry and immersion depth on the torque and drag force of a paddle wheel aerator using computational fluid dynamics (CFD-External flow) software. Their study found that lowest torque and drag force was achieved for the blade configuration having 30° blade angle, 1.6 cm hole diameter (hole on the blade surface) at an immersion depth of 4 cm. The authors inferred that blade profile should be designed in such way to reduce the drag force (frictional and pressure force acting parallel and perpendicular to blade surface respectively) which consequently reduces the torque. The torque is significantly affected by immersion depth. The torque increased with increasing immersion depth due to increase in drag force. Since power is a function of torque, increase in torque increases power consumption which in turn increase aeration cost. It is also suggested that CFD software (computer aided) will be helpful research tool for designing and performance evaluation of different paddle wheel blade configurations which reduces fabrication and testing procedure cost.

Bahri *et al*. (2015) [2, 3] designed a paddle wheel aerator with movable blades (cam operated, spring adjusted) and simulated it using CFD software to study the effects of various operational parameters on SOTR and SAE. Their study

Revealed that drag force was less for moving blade paddle wheel aerator compared to fixed blade paddle wheel aerator. Consequently, moving blade paddle wheel aerator leads to lower torque and power consumption. It was also reported that moving blade configuration produced more uniform velocity because of development of better flow pattern (due to lower drag force). The authors suggested that, this study may be taken forward by practically evaluating the performance of moving blade paddle wheel aerator and comparing it with conventional paddle wheel aerators in terms of SOTR, SAE, life time, capital cost, maintenance cost, etc.

Bahri *et al*. (2016) [4] designed and simulated the effect of moving blade paddle wheel aerator on power consumption and compared the result with conventional (fixed blade) paddle wheel aerator. Their study found that, even though torque was reduced in moving blade (bahri *et al*., 2015) [2, 3] configuration, power consumption still found to be higher than fixed blade configuration because of the friction generated between cam and follower (which was used to move the blades). By decreasing angle of contact between cam and follower, reduces the power loss due to friction. The reviewers recommended that while deigning aerators, number of mechanical moving parts should be as minimum as possible or better construction of mechanism in such way to reduce the friction.

Omofunmi *et al*. (2016) [17] developed a cost effective and efficient paddle wheel aerator prototype for small and medium sized ponds in Nigeria to improve the income of the fish farmers. The paddle wheel aerator was made up of stainless steel (paddles, paddle hub) and brass (shaft). It was reported that, Aerator was efficient for water volume upto 2 m^3. Thereafter, aerator efficiency decreased with increase in volume of water. The reviewers inferred that SOTR and SAE is a function of volume of water. Hence, volume of water to be aerated must take into consideration during designing of new aeration system in order to achieve required SOTR and maximum SAE.

Spiral wheel aerator

A spiral wheel aerator is a modified version of paddle wheel aerator, common example of surface aerator. Aeration is done on the pond or by constant splashing of air into the atmosphere by the spiral rotation. The spiral wheel aerator has the following parts: An electric motor – 1 No., a reduction gear box or a reducer – 1 No., connecting shaft – 2 Nos., A base frame – 1 No., anchor or aerator setting bar – 4 Nos., movable joints; engine cover – 1 No., Spines and floats (number of spines & floats depends on SOTR and SAE)

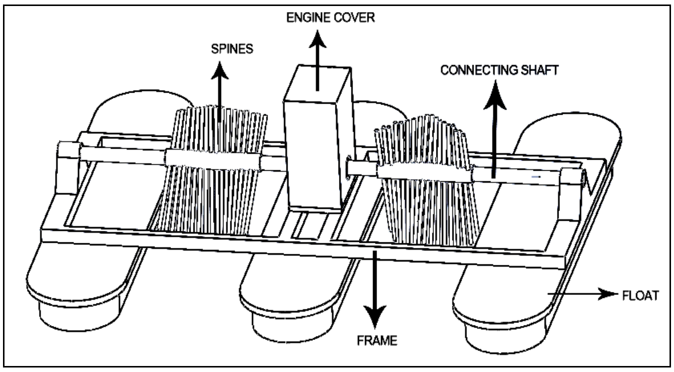

Fig 2: Spiral wheel aerator

Function

The continuous rotation of the spines attached with shaft splash the pond water. The spilled water particles make contact with atmospheric air and get back to the water surface. The oxygen molecule present in the air gets dissolved in the water which will increase the dissolved oxygen (DO) content of the pond water. Due to continuous splashing of water, temperature gradient will not be formed along the depth of the pond. The amount of oxygen gets dissolved depends on the length and speed of the spines. Thus longer the spines, amount oxygen dissolved level will be more. Besides, it will not allow any feed to settle down at the bottom of the pond.

Spiral wheel aeration in aquaculture water treatment

Bhuyar *et al*. (2009) [6] studied the effects of curved blade aerator on aeration efficiency, overall oxygen transfer coefficient and compared it with the result of computational fluid dynamics (CFD) model. The test was carried out in an oxidation ditch to treat municipal and domestic sewage. The maximum SAE obtained was 2.95 kg O_2/KWh. It was also concluded that the significance of backsplash was very high at higher rotational speed for the paddle wheel aerator. The development of CFD model can be helpful for analysis of flow velocity at various dynamic conditions in the aeration region. The authors inferred that SAE decreases with increase in rotational speed of the aerators.

Raza *et al*. (2016) [18] discussed about the literatures on screw conveyor and design of spiral aerator for earthen making process. Roy *et al*. (2017) [20] esigned and studied the performance characteristics of the spiral aerator to check its suitability for intensive aquaculture. The simulated equations were developed for oxygen transfer and power consumption based on non dimensional analysis. They also reported the optimum rotational speed of the aerators was 70 rpm for pond volume upto 700 $m^{3,}$ whereas for pond volume more than 700 m3, it was in the range of 120 – 220 rpm to achieve least aeration cost. From the study, the reviewers suggested that running the aerators at optimum rotational speed would yield higher SAE.

Table 1: Comparative performance of SAE for different surface aeration systems

S. No	Paddle wheel aerator types	Maximum SAE (kg O_2 / KW-h)	Authors	Year
1		1.95	Busch *et al*., (1984)	1984
2	Steel	2.95	Ahmad & Boyd, (1988) [1, 5]	1988
3	PVC	2.6	Boyd *et al*., (1988) [1, 5]	1988
4		2.54	Moore & Boyd, (1992) [13]	1992
5	Two impeller	3.46	Fast *et al*., (1999) [9]	1999
6	Taiwan model	1.188	Peterson & Walker, (2002)	2002
7	Curved blade	2.95	Bhuyar *et al*., (2009) [6]	2009
8		1.019	Roy *et al*., (2015) [20]	2015
9	Nigeria	1.3	Omofunmi *et al*., (2016) [17]	2016
10	Spiral	1	Roy *et al*., (2016) [20]	2016

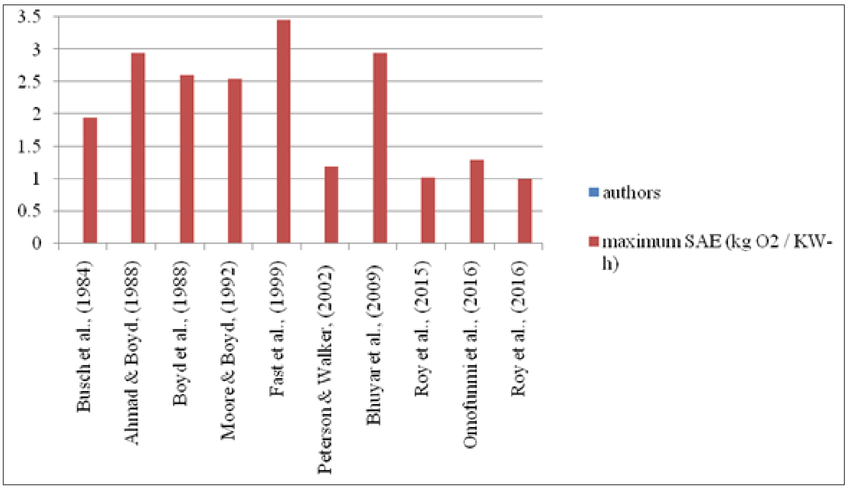

Fig 1: Variation in SAE of surface aeration systems

Conclusions

Dissolved oxygen is one of the important parameters in the aquatic production systems. In this present study, a comprehensive review has been carried out on paddle wheel and spiral aerators. Paddle wheel aerator is found to be the best due to its low cost, low maintenance, ease in operation and high SOTR as well as SAE in intensive pond culture systems. Thus, it can be concluded that properly operated aeration system will help to mitigate the environmental hazard in the intensive culture and also reduction energy cost. Hence, judiciously selected aeration system will contribute towards profit of the farmers. It is found that few literatures are available in spiral aerators. Therefore, more study about design and performance characteristics of spiral aerators could be carried out in future. By using computational fluid dynamics, different types of sturdy and shrewd aeration mechanism can be designed and its mixing characteristics and flow pattern can also be studied. It will reduce the design and testing cost.

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