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*Research Article*

# The effect of time delay of fluid flow in a vascularized plate

Onur Yenigün, Turgay Coşkun, Erdal Çetkin*

*Department of Mechanical Engineering, Izmir Institute of Technology, Izmir, Turkey*

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**Abstract**

In this study, we show the effect of time delay of coolant fluid flow into a vascularized plate on the peak temperature. Coolant flows along vascular channels which were embedded in a rectangular plate. Two kinds of vascular channel designs were investigated experimentally: parallel and tree-shaped. In the study, the peak temperatures were monitored and the coolant was pumped when the peak temperature reaches to 50°C, 70°C and 90°C. The performance comparison of two distinct designs is based on two criteria: the time required for the steady state condition after the coolant is pumped and the peak temperature after the steady state condition is conformed. The results show that the time required to reach steady-state condition increases as the time delay increases. The parallel and tree-shaped designs show similar performance (time required to reach steady state) with slightly improved performance in the tree-shaped design as the preset temperature for time delay increases. For instance, 4% decrease in the time required to reach steady-state with the tree-shaped design relative to the parallel design was achieved when the preset temperature for time delay is 90°C.

## 1. Introduction

The trend of compact equipment with high processing capability increases the volumetric heat generation rate greatly in the last decade. Compact equipment design constraint limits the increase of heat transfer surface area. Therefore, the literature focus on the maximization of the overall heat transfer coefficient (i.e., minimization of the thermal resistances) such as using nanofluids and phase change materials in order to enhance heat transfer rate [1-4]. Furthermore, not always the rate of generated heat is known, i.e. such as the case of thermal runaway. Therefore, there is a need for uncovering the performance of cooling systems with random heat generation cases. For instance, Cetkin et al. [5] uncovered numerically how the temperature distribution is affected when there is a randomly moving source on a vascular plate. Self-cooling structures promises to provide proper cooling of a structure even under random heat generation cases [5-12].

Materials with the smart feature of self-healing (autonomic healing) was firstly suggested by White et. al. [13] in 2001. They mimicked the healing mechanism of animals, i.e., clot seals the wound. Unlike in the animals, the suggested mechanism in their publication was to embed spheres filled with healing agent. Therefore, this healing could be achieved once, i.e. not repetitive. Later, Hamilton et. al. [14] stated that embedded vascular channels into the structure would create a network similar to the circulatory system which would yield countless time of healing in theory. However, the healing agent during the release may also block the channels which reduces the performance of healing for multiple healing cases.

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*Corresponding author: erdalcetkin@iyte.edu.tr
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Bejan et. al. [15] discussed that embedding vascular channels into a structure can also be used to cool it under an applied heat load. Wang et. al. [16] uncovered how the mechanical strength of a domain with a cavity shaped as the vascular channel network is affected for various vascular channel networks and volume fraction. Later, Cetkin et al. [10] uncovered how the mechanical strength and cooling performance are affected by the volume fraction and the shape of the embedded channel configurations simultaneously. In addition, Cetkin et. al. [5] showed that vascularization provides required cooling even when the cooling requirements are random [14]. Later, the publications uncovered the effect of thermal expansion on vascularized plates which are heated and under a mechanical load [17-18].

The current literature uncovers the cooling performance in steady-state condition. Therefore, fluid should be circulated in the vascular channels continuously. However, this would not be feasible due to the energy usage in random heating load cases. This paper discusses the effect of time delay of the fluid flow in order to uncover what should be the required time for delay when the equipment is heated with a random heat load. The parallel and tree-shaped vascular channel structures were investigated experimentally.

## 2. Model

The plates of size 170x170 mm with embedded vascularized cooling channels were heated with constant and uniform heating load of 150W from the surface boundary as shown in Fig. 1. The details on the length scales and geometry can be found in our previous publication [19], and the dimensions are also given in Table 1. The rest of the outer boundaries of the vascularized plate is adiabatic (i.e., $\partial T/\partial n=0$). Coolant flows along the embedded vasculature network with the same flow rate for all the designs (0.225 lt/min, Re =1198). The pressure difference between the inlet and outlet boundaries of the cooling channels is the driving force for coolant to flow. The volume of the vascular channels and solid plate are fixed for all the designs. The channel surface area for the tree-shaped and parallel designs are $0.013 m^2$ and $0.014 m^2$, respectively. In addition, the coolant is distilled water.

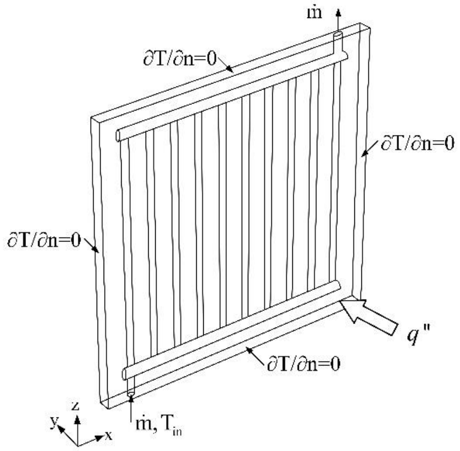
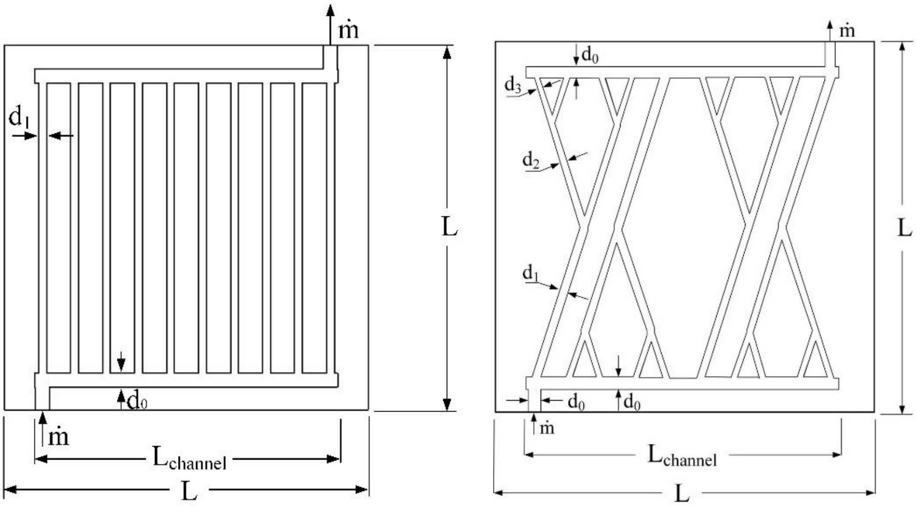


Fig. 1 Cooling plate with embedded circular cross-sectional channels in parallel design: boundary conditions with perspective of the geometry [19]

Two vasculature network is studied in the current paper: parallel design (Fig. 2a) and tree-shaped design (Fig. 2b). In the parallel design, the coolant channels of diameter $d_1$ are connected to one distributing and one collecting channels of diameter $d_0$. In the tree-shaped design, four cooling channels of diameter $d_1$ is joined to eight channels of diameter $d_2$ and they are connected to sixteen daughter channels of diameter $d_3$. All of the tree-shaped channels are connected to one distributing and one collecting channels of diameter $d_0$ with the channels of diameter $d_3$.



(a) (b)

Fig. 2 Cooling plate with embedded circular cross-sectional channels: (a) parallel design and (b) tree-shaped design [19]

Table 1 Dimensions of the competitive designs

| Designs | d0 [m] | d1 [m] | d2 [m] | d3 [m] | L [m] | L channel [m] |
|---|---|---|---|---|---|---|
| Parallel | 0.004 | 0.0025 | - | - | 0.17 | 0.15 |
| Tree-shaped | 0.004 | 0.003 | 0.0025 | 0.002 | 0.17 | 0.15 |

## 3. Experimental Method

Figure 3 shows the schematics of the experimental setup. The setup consists of cooled circulating bath, needle valve, turbine flow meter, thermocouples, vascularized plate, thermal camera, silicone flexible resistance and data logger. The circulating water bath regulates constant inlet temperature into the vascular channels. The temperature at the inlet of the vasculature network is also measured to check whether the temperature fluctuates. During the study we have monitored constant inlet temperature (i.e., the fluctuation in the temperature is in the order of the accuracy of the cooled circulating bath). Needle valve and flow meter are used to turn on/off the coolant flow and to measure volume flow rate of the coolant, respectively. Thermocouples were used to measure ambient temperature and coolant at the outlet of the vascular plate in addition to the inlet temperature of the coolant into the vasculature. The vascularized plates used in the experiments were manufactured from 5083 Aluminum. A silicone heater is used to supply constant heat flux to the bottom surface of the vascular plate. The overall heating rate of the silicone heater is 150W. Hioki data logger was used to record measurement data of the flow meter and thermocouples. The peak temperature on the surface was measured with thermal camera which was calibrated before the measurements. The accuracies of each measurement equipment with the error analysis study was given in our previous study of Ref [19] where the temperature distribution of the vascularized structure was documented under steady state condition (i.e., constant flow rate of the coolant supplied into the vasculature structure in the Ref. [19]).

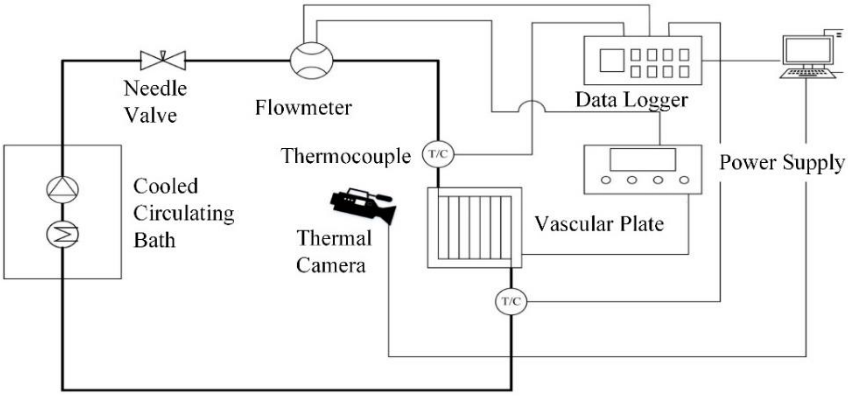


Fig. 3 The schematic of the experimental setup [19]

In the experiment, the coolant fluid in the water bath is cooled down to 20°C. Then, vascular plate was heated by using the silicone flexible resistance. First, there is no coolant flowing in the vasculature. Heating process is continued up to the pre-determined peak temperature value. Then, the needle valve was turned on to supply the coolant into the vasculature. The coolant flows through the needle valve, flow meter and vascular plate, respectively, and then it returns to the circulating bath. The volumetric flow rate of the coolant is 0.225 lt/min and the flow regime is laminar during the process (maximum value of the Reynolds number is 1198). The cooling power of the circulating bath (250W) is greater than the supplied heat from the silicone resistance (150W). Therefore, the inlet temperature of the coolant into the vascularized plate was kept constant. In addition, during the experiment, the maximum temperature on the surface of the plate is monitored via thermal camera. The temperature distribution on the thermal camera and measurements done from the thermocouples were monitored and stored. The experiment is repeated for various pre-determined peak temperatures such as 50°C, 70°C and 90°C. Finally, the required time to reach steady state condition is evaluated with respect to peak temperature values.

## 4. Results and Discussion

Here, the peak temperature history of the experimental results for two distinct vasculature structures (parallel and tree-shaped) are documented. In addition to the effect of design on cooling, the effect of the cooling time of the vascularized plates are investigated.

First, consider the parallel design of Fig. 2(a) with preset temperatures of 50$^{o}$C, 70$^{o}$C and 90$^{o}$C in order to supply the coolant. The applied heating load increases the temperature of the solid domain in which coolant is trapped, i.e. no flow of coolant. Therefore, the temperature increases in an S-curve characteristic as expected, cf. Fig. 4.

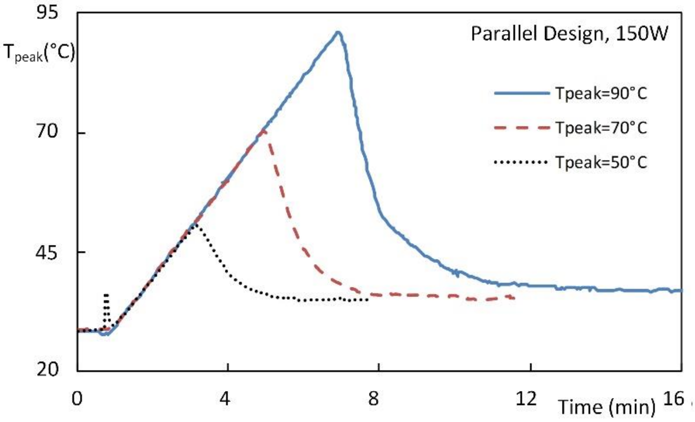


Fig. 4 Parallel design with preset temperature of 50°C, 70°C and 90°C

According to Figure 4, when the cooling fluid delayed, the time required to reach steady state condition increases due to the stored thermal energy in the vascularized plate. The plate reaches steady state condition in approximately 6min, 8min and 11min for the peak temperatures 50°C, 70°C and 90°C, respectively. Steady-state temperatures are approximately the same and measured as 35°C (there is a fluctuation in the order of 1°C due to the variation of the ambient temperature). This also indicates that the proper cooling at the circulating bath and the vasculature was achieved. Figure 4 also shows that the decrease in the peak temperature is steeper when the coolant is being sent to the vasculature. The temperature difference of the coolant flowing along the vasculature and the solid plate yield an exponential peak temperature difference history from the instance that the coolant is pumped to the steady-state condition temperature. Therefore, the peak temperature decreases in a steep fashion after the fluid is pumped until the peak temperature and steady state temperature difference is approximately 5oC.

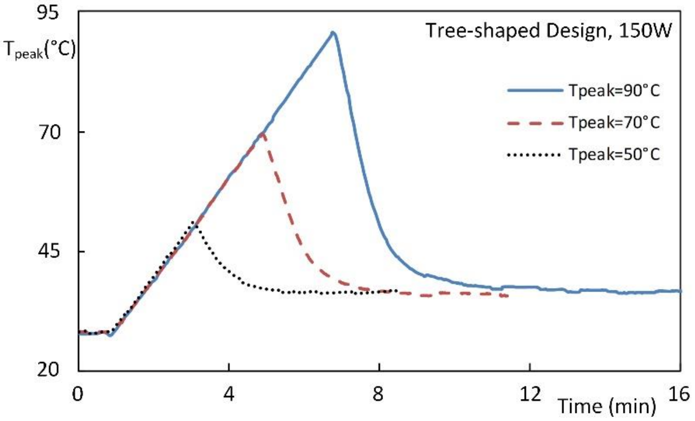


Fig. 5 Tree-shaped design with preset temperature of 50°C, 70°C and 90°C

Next, consider the tree-shaped design with three levels of embedded vascular cooling channels in Figure 2(b). Figure 5 shows that the temperature history from time 0 min to the preset temperature is almost the same with the temperature history of Fig. 4. Because the volume of the coolant and the solid material is fixed, this result is reasonable. They are not exactly the same due to how non-flowing coolant distributed inside the vasculature and the surface area of the channels are different in Figs. 4 and 5.

Figure 5 shows that the vascularized plate reaches steady state condition approximately in 5min, 8min and 10min for the peak temperatures 50℃, 70℃ and 90℃, respectively. Figures 4 and 5 shows that the time required to reach steady state is approximately the same for both parallel and tree-shaped designs. However, the results indicated that the steady-state temperature is being reached faster with the tree-shaped design. The reason of that trend is due to the decrease of the pressure drop in the tree-shaped design relative to the parallel design. Steady-state temperatures were recorded as approximately 36℃ for the peak temperatures 50℃, 70℃ and 90℃. In addition, the steady state peak temperature is 1℃ greater in tree-shaped design relative to the parallel one. However, this difference stays in the calculated error for the experimental analysis.

## 5. Conclusions

In this study, we showed the effect of time delay on the cooling of a vascularized plate with two distinct channel networks: parallel and tree-shaped designs. The results show that varying the time delay affects the peak temperature, and that the time required to reach steady-state condition is increased by the rise in peak temperature. The temperature history first shows an S-curve characteristic (from time 0 to peak temperature) and then it shows an exponential characteristic (from the peak temperature to the steady-state temperature). Figures 4 and 5 uncover that the time required to reach steady-state condition increases approximately 1 min for every 10°C increment. However, it should be noted here the cooling power of the circulating bath is greater than the supplied heat load. Therefore, the supplied coolant satisfied the requirement of constant temperature at the inlet of the vascularized structure. Otherwise, the steady-state may not be reached. The results show that the parallel and tree-shaped designs yields almost the same steady state temperature (1$^{o}$C difference exists which is less than the experimental error). However, the steady state temperature is reached faster with the tree-shaped design. For instance, it is 4% less than the parallel design when the preset temperature for time delay is 90°C.

## Acknowledgment

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