



Multiphysics topology optimization scheme considering the evaporation cooling effect

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ABSTRACT

In this research, a new topology optimization scheme considering the evaporation cooling effect that cools air through the evaporation of liquid is presented. To efficiently cool down hot surfaces or products, it is a viable approach to use the evaporating cooling effect when water absorbs a large amount of heat on evaporating. To numerically consider the evaporating cooling effect, the three nonlinear governing equations, i.e., Navier–Stokes equation, heat transfer equation, and moisture transportation, should be coupled and analyzed; Air movement, temperature convection, and moisture transportation should be mutually coupled and analyzed. Due to the movement of air, the moisture inside porous media evaporates and the velocities, temperature, and moisture distributions of porous media are subject to be changed. From a topology optimization point of view, the material properties as well as the governing equations are interpolated with respect to the design variables defined at each finite element. After solving topology optimization problems, it is possible to find out the optimal distributions of porous media to control the states of the system. Through several numerical examples, the validity of the present topology optimization method is illustrated.

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1. Introduction

The present study develops a new topology optimization scheme for optimal heat dissipation structures considering the heat adsorption and the heat absorption supplied or extracted to change the state of water (See [1–3] and references therein). To cool down hot surfaces or devices, the heat dissipation through force or natural convection is a common approach. When the large amount of energy should be removed and the use of environmentally friendly technology is strongly encouraged, it is also a viable approach to use the evaporating cooling effect absorbing a large amount of heat as shown in Fig. 1. To numerically simulate the evaporating cooling effect, the three governing equations, i.e., Navier–Stokes equation, heat transfer equation, and moisture transportation, can be coupled and analyzed; Air movement, temperature convection, and moisture transportation are mutually coupled and analyzed. As a substance changing phase, this research considers moisture inside porous media. Due to the movement of air, the moisture inside porous media evaporates and the thermodynamics of porous media are changed. Apart from the current challenges for each of these simulations, future perspectives should be directed towards material property determination and

model validations for optimization. From a topology optimization point of view allowing free material distribution, the material properties as well as the governing equations are interpolated with respect to the design variables at each finite element. To our best knowledge, from the topology optimization point of view, this subject has not been researched yet. After presenting a modification of the multiphysics problem and solving topology optimization problem, it is possible to find out the optimal distributions of porous media to control the thermodynamic states of the system.

Through topology optimization scheme, some unanticipated optimal layouts can be found for complex engineering structures. For topology optimization with a gradient based optimizer, the design variables interpolating the material properties of physics of interest using the Solid Isotropic Material with Penalization (SIMP) scheme are assigned to each finite elements. This topology optimization scheme has been successfully applied for many multiphysics systems [4–13]. To our best knowledge, the topology optimization considering the evaporation cooling effect requiring the multiphysics analysis among fluid, heat transfer, and transportation of moisture has not been conducted before this research. In [12], the Stefan problem for solidification with finite element method is solved for topology optimization for heat transfer enhancement in latent heat thermal energy storage. The structural optimization for heat related system was conducted in many

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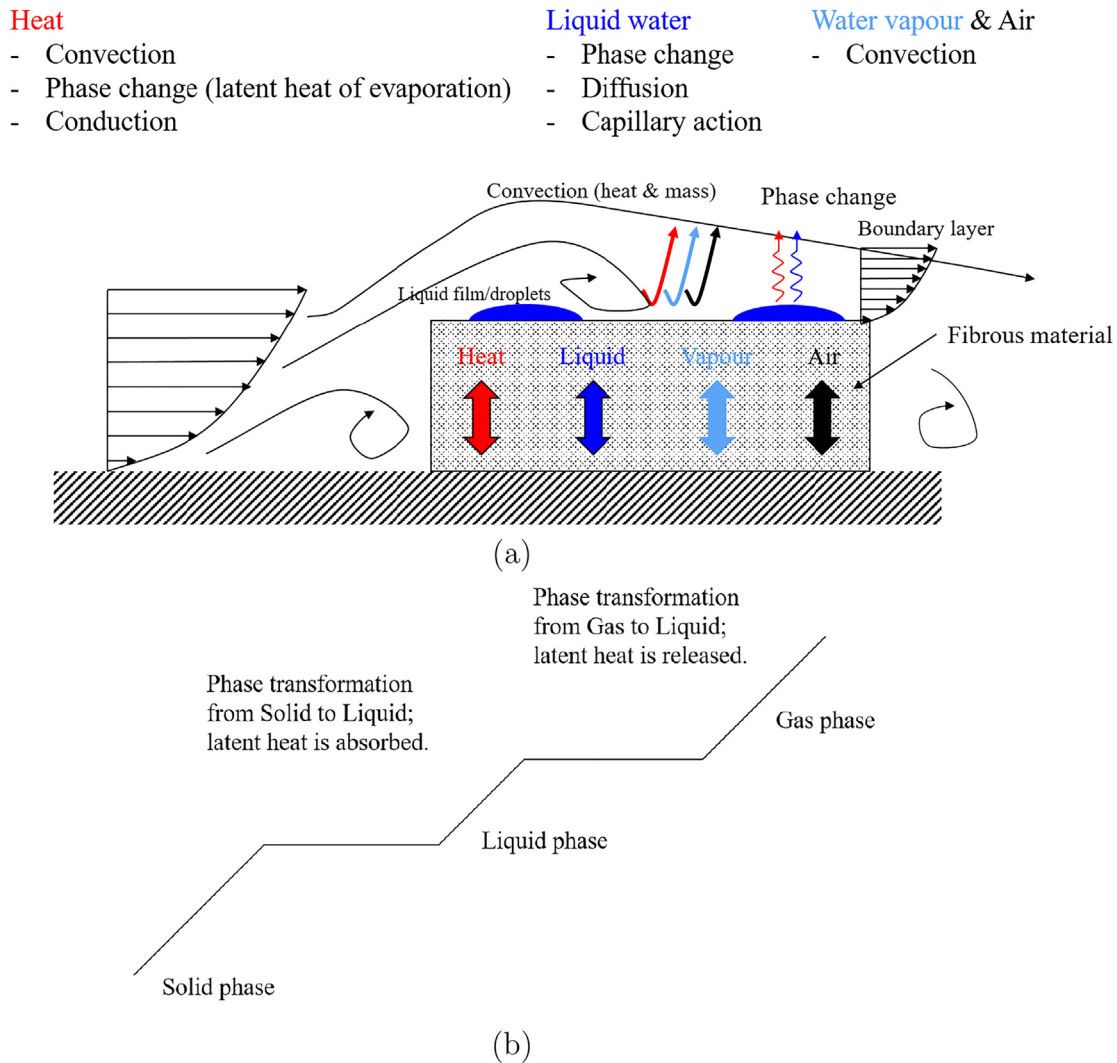


Fig. 1. Multiphysics analysis of evaporation (a) heat, liquid (moisture), water vapour and air movement in fibrous material and (b) the latent heat depending on material phase.

researches (See ([13,6]) and references therein for the review). In [7], the thermoelastic topology optimization with varying temperature field was proposed. Using the level-set approach, the heat conduction problem was optimized in [8,9]. The fluid and heat transfer systems have been studied in [10,14,15]. In [16], the topology optimization solver was developed to optimize the conjugate heat transfer problem by minimizing pressure losses and maximizing the heat transfer. In [15], the topology optimization in thermal-fluid flow using the lattice Boltzmann method was researched. In [17], the topology optimization using the level set approach was researched. To our best knowledge, the energy transform due to the change of phase or the transportation is rarely considered in the topology optimization. In [18], a review of on-chip micro-evaporation is provided. In [19], the application of the topology optimization of liquid-cooled micro-channel heat sinks is numerically and experimentally validated. In [20], the topology optimization method considering pressure drop reduction and thermal power maximization is developed using an opensource CFD platform via finite volume method. In [21], the topology optimization of conjugate heat transfer system and phase change material is developed for latent heat thermal energy storage. Several pareto designs maximizing the performance of heat exchanger are obtained and compared considering discharged energy and

discharge time. To our best knowledge, the energy transform due to the change of phase or the transportation is rarely considered in the topology optimization.

The evaporation cooling has been employed for many science and engineering applications. When water changes its states i.e., from fluid to moisture or from moisture to fluid, heat energy called the latent heat (the hidden energy when changing phases) is supplied or extracted. A simple example of evaporation cooling is sweat or perspiration after excises. With this evaporation of water, body temperature can be decreased. The energy of heat loss due to the evaporation depends on the evaporation rate and the evaporation itself depends on the ambient temperature and humidity of air. Due to its large energy dissipation, many industrial applications can be found (See [1–3,22] and references therein). For example, the evaporation cooling has been used for air condition system or vapor-compression refrigeration in order to reduce the power in operation and increase its capacity and the overall efficient. Using the heat loss during evaporation, it is possible to build a clean cooling device for air conditioning system. As the efficiency of cooling device varies depending on the ventilation of air and the water distribution, many researches have been conducted to determine a novel water spray configuration and thermal configuration. As the numerical simulation of the evaporation cooling requires a

multiphysics theory, there are a few researches applying optimization scheme or theory for sophisticated design for an effective heat device. The heat and mass transfer in porous media in the food processing was studied [1]. The transient formulas of the most fundamental to the semi empirical have been investigated in food processing examples. However, the optimization and the latent heat by flow were not studied. The heat and mass transfer in porous media is also important from a perspective of the drying (dehydration or dewatering) process [3,2]. Removing moisture from nature or industrial materials is essential as the production time and quality can be shortened and improved. Particularly the drying becomes important for processing food, textile, paper, wood, ceramic, minerals or biotechnological products. Although it is important to optimize the process of drying technologies, the simulation and experimental studies are required due to the complexity of the state-of-the-art technologies. During the exchange process of drying, note that the latent heat becomes an important factor. The mechanical behavior during drying can be simulated.

The analysis procedures depending on the size of pores are reviewed in [1]. For large pores and applied pressure, the Navier–Stokes analog of Darcy equation, the energy equation and the species equations are solved. For small pores, pressure mostly from internal evaporation, the Darcy equation replacing momentum equation, the energy equation and the species equation for each phase are simultaneously solved. For small pores, capillarity, no significant evaporation, the Darcy equation for capillary pressure and species equation for liquid phase are solved. For small pores, capillarity plus other modes, semi-empirical formulation with effective diffusivity for a combined species equation or energy equation with empirical evaporation terms. The present study adopts the model with Navier–Stokes analogy with Darcy's equation, energy equation and transport equation.

For topology optimization process, this research simulates the evaporation cooling effect using the finite element procedure. It is assumed that a system is at steady-state simplifying not only the analysis procedures for the primarily variables and the sensitivity but also the optimization formulation. To analyze the steady-state evaporation cooling, the Navier–Stokes equation for laminar flow, the conjugate heat transfer equation, and the transportation of moisture in porous media should be solved simultaneously. To represent the states of porous media and fluid media depending on the design variable simultaneously, the governing equations should be modified. In the Navier–Stokes equation, the Darcy's force is added to model the fluid in porous media and parameterized with respect to the spatial design variables (the constant design variables at each finite elements). In the conjugate heat transfer equation, the parameterization of the involved material properties and the latent heat source with respect to the design variables should be formulated. For the transportation equation, the effective diffusion coefficients are interpolated with respect to the design variables. The objective function is formulated considering the fluid dissipation energy, the internal thermal energy

and the moisture of porous material. Through this development, the effect of the evaporation can be considered in the framework of topology optimization.

The paper is organized as follows. Section 2 provides some backgrounds to the optimization of the fluid-thermal-moisture coupling system and describes the governing equations for the multiphysics system considering the latent heat. In Section 3, several optimization studies are considered and the structural optimization results are presented. Section 4 provides the conclusions and suggestions for future research topics.

2. Fluid-thermal-moisture coupled analysis and topology optimization

This section summarizes the theories and assumptions of the multiphysics analysis of fluid, thermal, and moisture and develops the topology optimization procedure. As stated, the simulation of the evaporation heat loss requires the multiphysics analysis, where conjugate heat transfer, mass and momentum transport processes occur inside porous material and also the exchange processes of thermal energy and moisture with environment take place at air-porous material interfaces. Several engineering applications of this multiphysics system can be found in food engineering and printing engineering. For example, the drying of food or the control of the moisture inside food is an important issue and the curl issue (the deflection of fibrous paper caused by the moisture transportation) in laser printer is also important issue. Without the loss of generality, monolithic or segregated approaches for the multiphysics system can be employed [3]. From a topology optimization point of view, the material interpolation of the involved material properties needs to be formulated to model fluid as well as porous material followed by the detailed topology optimization procedure and the sensitivity analysis.

2.1. Governing equation: desorption and absorption moisture

An overwhelming amount of literature are available for the latent heat of vaporization (see [1–3,22–24] and references therein). In food and paper printing industry, the strong coupled simulation of water evaporation in porous media is important to predict moisture distributions inside their products. For example, it is known that paper curl is influenced by the moisture transportation in the paper thickness direction (about $110\ \mu\text{m}$) and by the path trajectory of paper as shown in Fig. 2(a). In order to prevent/avoid jams for enhancing printing quality, it is important to simulate and reduce these unwanted curls. As the moisture transports in the thickness direction, i.e., about $110\ \mu\text{m}$ for a very short time, it is impossible to measure the amount of moisture transportation even with the state of the art measurement technologies entailing numerous problems. For this reason, it is crucial to develop a numerical simulation of moisture transportation, tem-

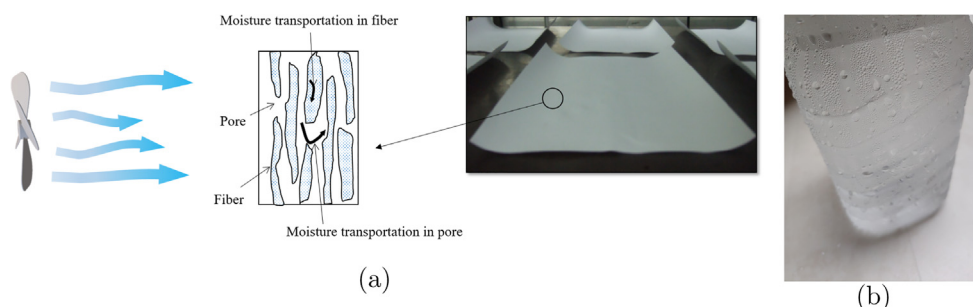


Fig. 2. Examples of heat and moisture evaporation. (a) Evaporation of paper and (b) water at glass.

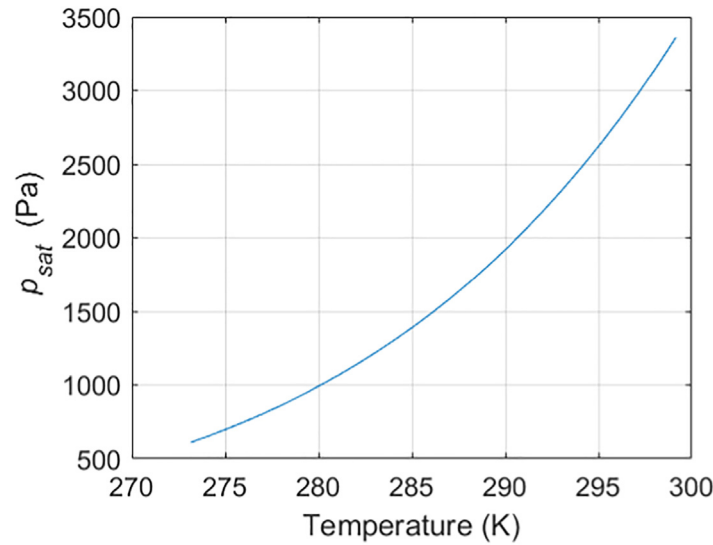


Fig. 3. Saturation curve.

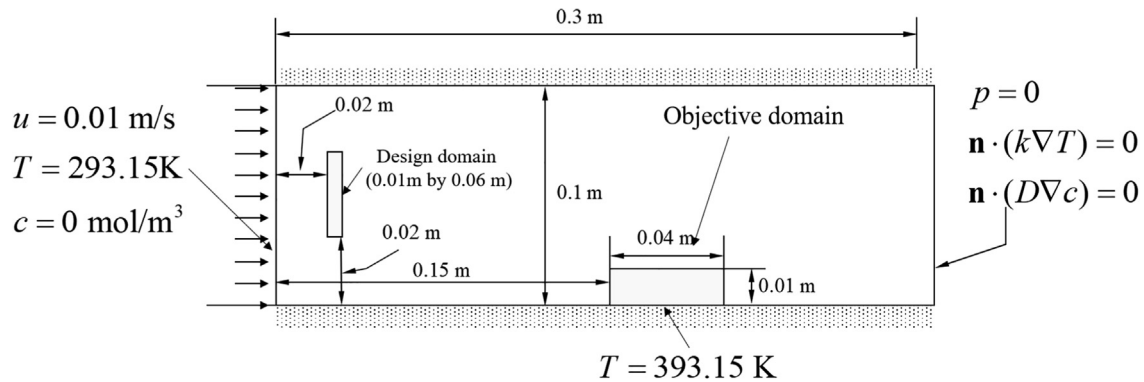


Fig. 4. Example 1. A channel design for the latent heat loss (Fluid air: density = 1.2043 kg/m³, viscosity = 1.8140 × 10⁻⁵ Pa·s. Porous material: density = 1528 kg/m³, permeability = 1 × 10⁻¹³ m², thermal conductivity = 0.21 W/(mK), heat capacity = 1650 J/(kg K), porosity = 0.4).

perature gradient and mechanical deformation. As an example of water evaporation, it is possible to observe the water seeping out from mushroom during your cooking as shown in Fig. 2(b). The water above mushroom during cooking comes from mushroom itself, i.e., the moisture transfer inside mushroom. Another example of water evaporation may be the cooling hot surfaces with the help of the water evaporation. As the result of a phase change and a transportation of water, heat can be absorbed or released. During the phase change and the moisture transportation, the kinetic energy within the molecules is not changed but the potential energy stored in atom bonds is released as the form of the latent energy. There are the condensation, the freezing, and the deposition as some examples for warming process called an exotherm process. For cooling process called endothermic, there are the evaporation/boiling, the melting, and the sublimation. In order to simulate these evaporation phenomena, the strong coupling simulations among fluid flow, heat transfer and transport of participating fluids and gases need to be solved. To consider the latent heat loss, the present study provides a numerical framework modeling the water transportation of porous materials.

Consider a porous material system, i.e., paper, food or fiber, with a surrounding air gas system. Employing the principles of irreversible thermodynamics, the theory of mass and heat transfer inside capillary-porous body with air cavities can be formulated. The temperature and moisture potential gradients within a

capillary-porous body should be considered as the sources of the vapour diffusion and transfer of liquid water. To numerically simulate these transportation phenomena, the effective medium approximations modeling the macroscopic properties of composite materials can be employed by averaging the involved material properties considering porous media or composite material. Several effective medium approximation models have been developed (see [1–3] and references therein) and most of them assume that the macroscopic system can be mathematically modelled by homogeneous media with the material properties corrected or modified by considering the microscopic geometries.

From a physical point of view, moisture may be absorbed or desorbed (evaporated) for porous media by changing temperature or humidity in the pores (air cavity) as shown in Fig. 4. The desorbed moisture transports by diffusion through pore space and the moisture diffusion through fibers can be ignored due to a lower diffusivity in porous. With high humidity in pores, the moisture in air cavities can be absorbed into the fiber again. For the analysis, first of all, the Navier–Stokes equations of porous domain and fluid domain are formulated as follows:

Porous domain :

$$\frac{1}{\epsilon_p} \rho (\mathbf{u} \cdot \nabla) \mathbf{u} \frac{1}{\epsilon_p} = \nabla \cdot \left[-p \mathbf{I} + \mu \frac{1}{\epsilon_p} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) - \frac{2}{3} \mu \frac{1}{\epsilon_p} (\nabla \cdot \mathbf{u}) \mathbf{I} \right] - (\mu \kappa^{-1}) \mathbf{u}$$

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

(1)

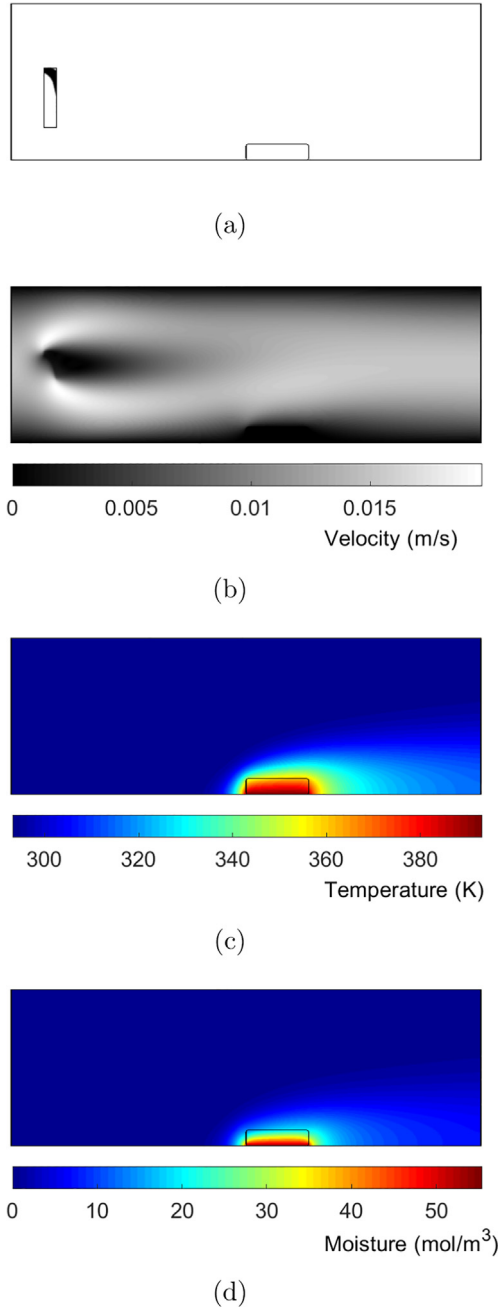


Fig. 5. Example results: (a) optimized design with 50% mass (objective = 0.1497 Km²), (b) velocity distribution, (c) temperature distribution and (d) moisture distribution.

where the porosity of porous material, the density, the velocity vector, the pressure, the dynamic viscosity, and the permeability are denoted by ε_p , ρ , \mathbf{u} , p , μ , and κ , respectively. The spatial differentiation is denoted by ∇ . The identity matrix is denoted by \mathbf{I} .

The Navier–Stokes equation for fluid domain with 1 for the fluid porosity, ε_p , which can be regarded as a simplified version of the above Navier–Stokes equation for porous medium as follows:

$$\begin{aligned} \text{Fluid domain :} \\ \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu(\nabla\mathbf{u} + \nabla\mathbf{u}^T) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I}] \\ \nabla \cdot (\rho\mathbf{u}) = 0 \end{aligned} \quad (2)$$

The mass transportation equation inside fluid and porous material can be formulated with diffusion and convection as follows:

$$-\nabla \cdot (D_{\text{eff}}\nabla c) + \mathbf{u} \cdot \nabla c = 0$$

where the effective diffusion coefficient and the concentration are denoted by D_{eff} , and c , respectively. In porous body, the diffusion coefficient for water vapor into air D_{eff} (m/s) can be modelled considering the porosity (Bruggeman model) as follows:

$$D_{\text{eff}} = \frac{\varepsilon}{\tau_L} D_L = \varepsilon^{3/2} D_L \quad (4)$$

where the porosity and the tortuosity are denoted by ε and τ_L , respectively. The diffusion coefficient for water vapor into air is denoted by D_L . The heat transfer equation for porous and fluid domains is formulated as follows:

$$\text{Fluid domain : } \rho C_f \mathbf{u} \cdot \nabla T - \nabla \cdot (k_f \nabla T) = 0 \quad (5)$$

$$\text{Porous domain : } \rho C_p \mathbf{u} \cdot \nabla T - \nabla \cdot (k_{\text{eff}} \nabla T) = -H_{\text{vap}} \times m_{\text{evap}} \quad (6)$$

$$k_{\text{eff}} = \theta_p k_p + (1 - \theta_p) k_f \quad (7)$$

where the capacity and the conduction coefficients of air are denoted by c_f and k_f , respectively. Those of porous domain are denoted by c_p and k_{eff} , respectively. The latent heat source is denoted by $-H_{\text{vap}} \times m_{\text{evap}}$. The temperature is denoted by T and the volume fraction in the porous media is θ_p .

In the above Eq. (7), the evaporation process is formulated by adding the mass of water vapor in the transport equation; water can be evaporated from fibrous material or can be reentered to fibrous material. The evaporated fluid, m_{vap} is dependent on the saturation pressure and the saturation pressure in Fig. 3 can be formulated as follows:

$$\begin{aligned} c_{\text{sat}} &= \frac{p_{\text{sat}}(T)}{RT} \\ p_{\text{sat}}(T) &= 610.7 \times 10^{7.5 \left(\frac{T-273.15}{T-35.85} \right)} \end{aligned} \quad (8)$$

where the saturation pressure is denoted by p_{sat} and the ideal gas constant $R = 8.314 \text{ J}/(\text{mol} \cdot \text{K})$. The amount of evaporated water is formulated as follows:

$$\begin{aligned} m_{\text{vap}} &= K(c_{\text{sat}} - c) \\ m_{\text{vap}} &\geq 0 \text{ when } c_{\text{sat}} \geq c \\ m_{\text{vap}} &\leq 0 \text{ when } c_{\text{sat}} \leq c \end{aligned} \quad (9)$$

where the evaporation rate and the current concentration are denoted by K and c , respectively. The heat due to the evaporation process, called the latent heat loss, is computed as follows:

$$Q = H_{\text{vap}} \times m_{\text{vap}} \quad (10)$$

where the latent heat of evaporation is denoted by H_{vap} , respectively.

2.2. Topology optimization formulation

To allow the topology optimization considering the latent heat of evaporation, the material interpolation scheme should be developed properly. The design variables, γ , are assigned to each finite elements. With the conventional segregated analysis approach using the different governing equations for fluid and porous domains, the above different governing equations are differently defined for each domain for computation. With that approach, it is impossible to change the governing equations from those of porous domain to those of fluid domain and vice versa. Therefore, to allow the free material design inside design domain, a unified governing equation approach should be employed; modifying the involved material properties rather than modifying the involved governing equations. To make it possible, the present study found

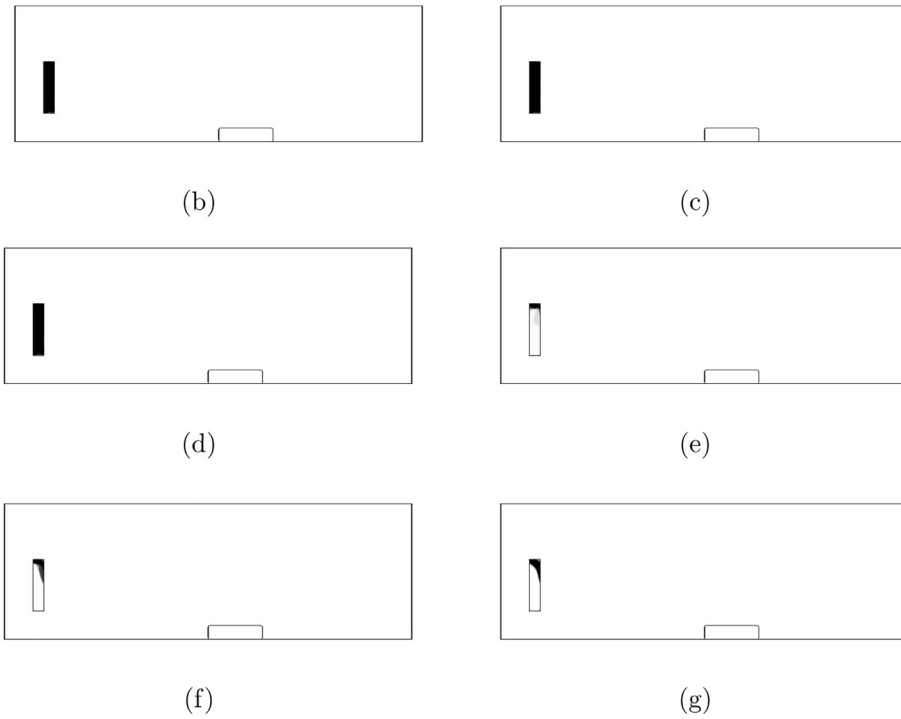
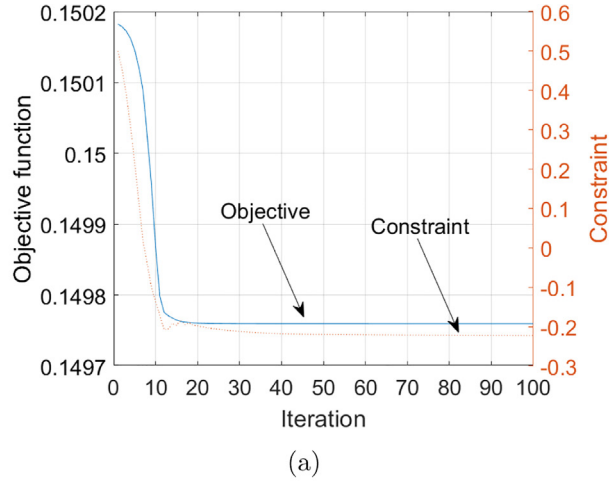


Fig. 6. Example 1 results: The intermediate design variables at 1st, 5th, 7th, 10th, 15th, and 100th iterations.

out that the governing equations for porous domain can be a platform and the material properties are subject to be changed to those of the fluid domain in order to modify and adjust the governing equations to those of the fluid domain. Without the loss of generality, the governing equations of the porous domain can be used for the unified governing equations as follows:

$$\frac{1}{\varepsilon} \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[-p \mathbf{I} + \mu \frac{1}{\varepsilon} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) - \frac{2}{3} \mu \frac{1}{\varepsilon_p} (\nabla \cdot \mathbf{u}) \mathbf{I} \right] - \alpha \mathbf{u}$$

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (11)$$

$$\rho C_p \mathbf{u} \cdot \nabla T - \nabla \cdot (k \nabla T) = \text{Heat source} \quad (12)$$

$$-\nabla \cdot (D \nabla c) + \mathbf{u} \cdot \nabla c = 0$$

Compared with the original Navier–Stokes equation of porous domain, the Darcy force $\alpha \mathbf{u}$ is added. One of the benefits of the

above unified governing equation is that the porosity, the permeability, and the Darcy's force can be interpolated rather than changing/alternating the governing equations.

To interpolate the governing equations for porous domain and fluid domain, the involved material properties can be interpolated as follows:

$$\varepsilon = \varepsilon_p \gamma^n + \varepsilon_f (1 - \gamma^n) \quad (14)$$

$$\kappa = \kappa_p \gamma^n + \kappa_f (1 - \gamma^n) \quad (15)$$

$$\alpha = \alpha_{max} \gamma^n \quad (16)$$

$$k = k_p \gamma^n + k_f (1 - \gamma^n) \quad (17)$$

$$D = D_p \gamma^n + D_f (1 - \gamma^n) \quad (18)$$

$$\text{Heat source} = -H_{vap} \times m_{evap} \times \gamma^n \quad (19)$$

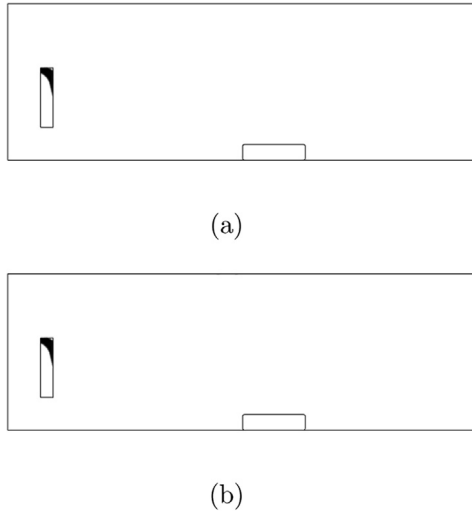


Fig. 7. Example results: (a) optimized design with 4 for n (objective = 0.1497 Km^2) and (b) optimized design with 5 for n (objective = 0.1497 Km^2).

where the material properties of fluid and porous are denoted by adding the subscripts, f and p , respectively. The penalization of the SIMP method is denoted by n . The design variables, γ , are assigned to each finite elements inside design domain. With zeros for the design variables, the corresponding elements represent fluid domain and oppositely with ones for the design variables, the cor-

responding elements represent pseudo rigid domain. Therefore, it is possible to optimize the variables to maximize or minimize objective functions subject to constraints. In the present study, the SIMP approach is employed rather than RAMP or other interpolation functions. However, it is also possible to use another interpolation function to interpolate the solid and void states. Also note that the values of the penalization factors influence the optimization results too. This implies that the layouts presented in the next section are local optima and several different layouts can be obtained. The fluid system is discretized by the second order shape function for the velocities and the first order shape function. The first order shape function is employed for the temperature and the transportation equation. The constant design variables are assigned to each finite elements. To simulate the coupled system, the Newton–Raphson iteration is employed. In the optimization process, some instabilities such as non-convergences of the Newton–Raphson scheme, the mesh-dependency and the local optima issue the can appear. In our numerical test, the value of α_{max} is one of the most important parameters causing the instabilities in the optimization. With a too large value for α_{max} , some isolated and nonphysical islands can appear and a smaller value for α_{max} is recommended. In our numerical test, n is set to 3 and α_{max} is set to 100. s

3. Optimization results

To validate the concept of applying topology optimization to design fluid-thermal-moisture system, this section solves some

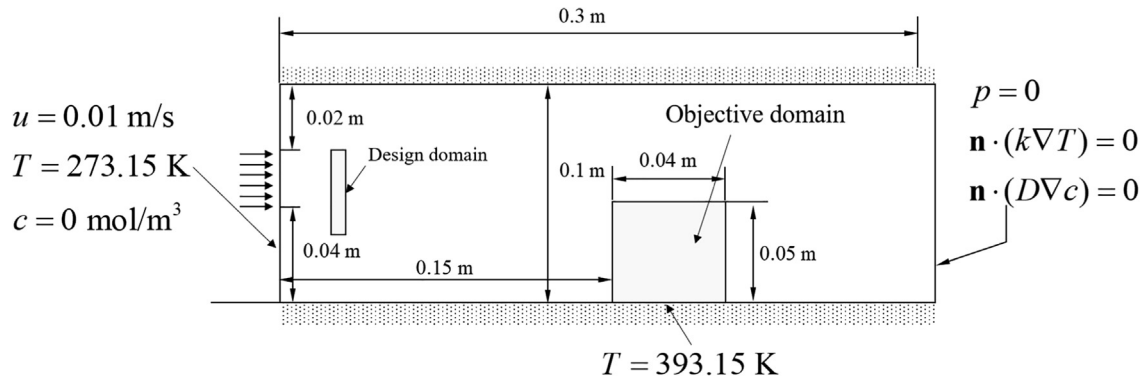


Fig. 8. Example 2. Fluid Air: density = 1.2043 kg/m^3 , viscosity = $1.8140 \times 10^{-5} \text{ Pa}\cdot\text{s}$. Porous material: density = 1528 kg/m^3 , permeability = $1 \times 10^{-13} \text{ m}^2$, thermal conductivity = 0.21 W/(mK) , heat capacity = 1650 J/(kg K) , porosity = 0.4).

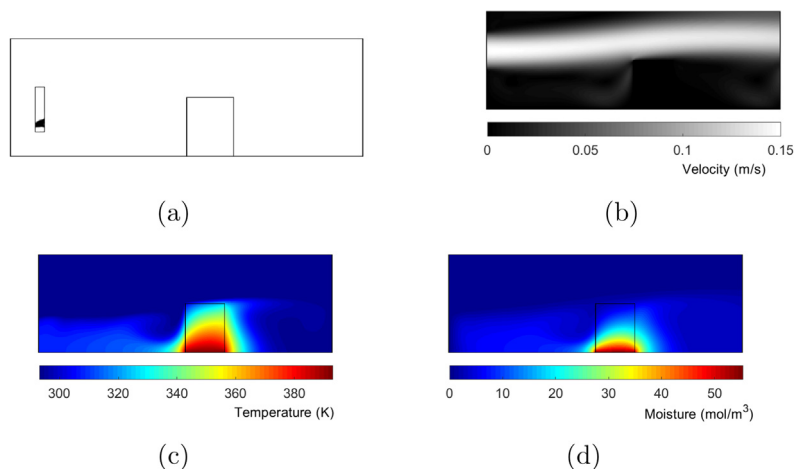


Fig. 9. Example 2 results: (a) an optimized design, (b) velocity distribution, (c) temperature distribution and (d) moisture distribution.

optimization problems considering the latent heat effect. In order to solve the optimization problem, the method of moving asymptotes (MMA) algorithm in the script finite element simulation environment is employed [25,26].

3.1. Example 1: Channel design Problem 1

For the first example, the optimization problem maximizing the heat loss of a specified domain temperature subject to the mass constraint is considered in Fig. 4; the objective function is the integration of the temperature over the center rectangular domain (Ω_0 : 0.04 m by 0.01 m) and the mass constraint is imposed in (20). By distributing the spatial materials at the left design domain and increasing the magnitude of fluid velocity for enhanced latent heat as well as for much enhanced forced convection, it is expected that an optimal layout cooling down the rectangular center domain can be found. The heat loss is caused by the evaporation (the latent heat) as well as the forced convection. From an optimization point

of view, it can be postulated to have a channel shape design to guide the fluid flow towards the center domain.

$$\begin{aligned} & \text{Min}_{\gamma} \int_{\Omega_0} T dx \\ & \text{Subject to } \text{Mass} \leq \text{Mass}_0 \\ & \gamma = [\gamma_1, \gamma_2, \dots, \gamma_{N_e}], \quad \gamma_{\min} \leq \gamma \leq 1 \end{aligned} \quad (20)$$

where the objective function is the integration of the temperature at the objective domain Ω_0 . The fluid moves from the left side with 0.01 m/s to the right outlet. The center porous material contains 0.95914 mol/m³ initial moisture. The design domain is set to the box located just after the fluid inlet. The center domain can be cooled down by the heat losses from the convective heat loss and the latent heat loss. The rigid wall boundary conditions (thermal insulation for temperature, rigid wall for fluid, and no flux for moisture) are imposed along the top and the bottom boundaries and the fixed temperature, 394.15 K, is imposed at the bottom of the objective domain. It is expected that the heat loss can be improved by the evaporation and the forced convection. The optimized layout in

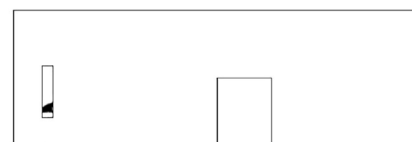
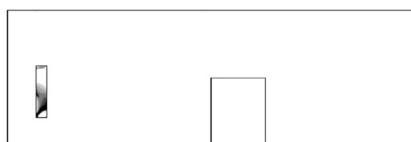
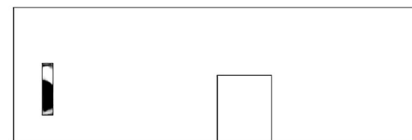
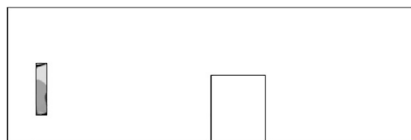
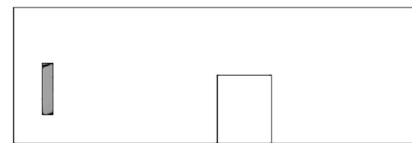
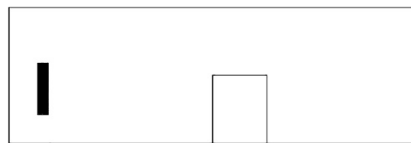
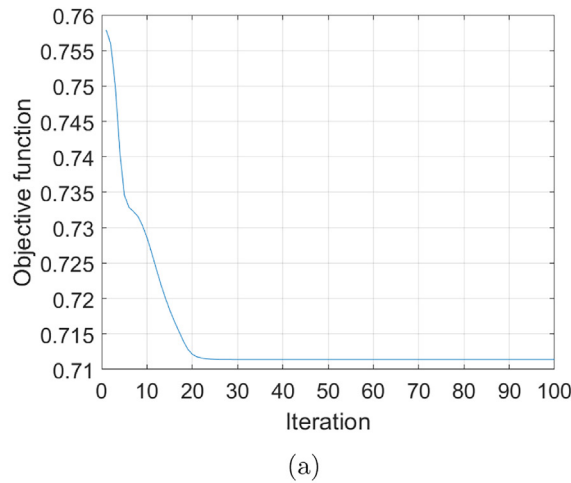


Fig. 10. The intermediate design variables at 1st, 5th, 7th, 10th, 15th, and 100th iterations.

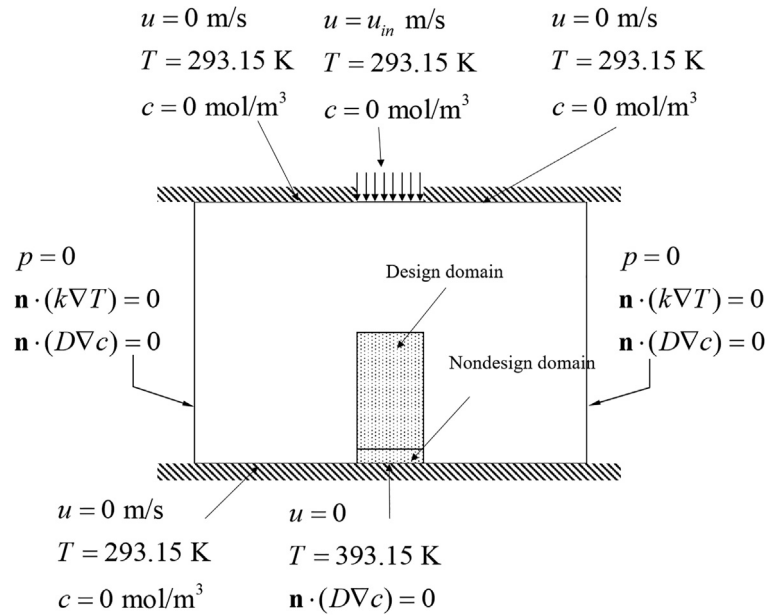


Fig. 11. Example #3: (a) 2-D domain with representative loads and boundary conditions.

Fig. 5 with the 27.78% mass can be obtained with the 50% mass constraint; the mass constraint is not active and the optimization algorithm determines the optimal mass ratio. The optimized structure is similar to the fin shape or the wing shape cross section which is an expected structure to maximize the heat loss by the forced convection and the latent heat loss. The optimization history and the intermediate designs are summarized in Fig. 6. Note that the improvement of the objective function is marginal due to the problem definition; the temperature is almost homogeneous at the domain. Several parameters in the topology optimization formulation affect the optimization result. To test the effect of the SIMP penalization, n , the optimal layouts with the different values are presented in Fig. 7. As illustrated, the similar layouts are obtained in this specific example with the similar objective values. However, note that the present optimization layouts are local optima and some different local optima can be obtained for different conditions.

3.2. Example 2: Channel design problem

For the next example, the channel design problem in Fig. 8 is considered without the mass constraint; the optimizer should determine an optimal mass usage. Compared with the first example, the temperature of the input flow is decreased to 273.15 K and the objective domain (porous domain) is enlarged in order to increase the heat loss. Due to the increased objective domain and the boundary conditions, the slit shape design can be obtained with 31.8433% mass in Fig. 9. With the low temperature of the input flow, the significant improvement in the objective function can be observed by the optimized structure. The optimized design changes the direction of the input flow to maximize the force convection and the latent heat loss. This result shows that the developed framework can be used in the design considering the fluid-thermal-moisture coupling system (see Fig. 10).

3.3. Example 3: Channel design problem

For the third example, we work through the channel design problem shown in Fig. 11. The purpose of the optimization problem is to find an optimal topology to maximize the heat dissipation by changing the flow distributions and the optimal distribution of

the porous medium. To introduce the developed topology optimization scheme, the domain is divided into the three domains: fluid domain, porous domain (non-design domain) and porous domain (design domain). As the flow direction affects the integral of temperature, new designs with different flow directions with the help of structure provide the opportunity to outperform the design without structure.

In the previous examples whose design domain is set to change the flow direction to improve the objective functions. However, in this example, the design domain is set to make it possible to change the material itself. In other words, by changing the material properties through the SIMP interpolation functions, it is intended to change the governing equation from that for fluid to that for fibrous material and vice versa. Therefore, the optimization algorithm should find out the interface between porous and fluid.

As the optimization of porous domain is pursued, structures in this example now can contain moisture. For this, it is noted that the permeability in the Navier-Stoke's equation of porous medium should be modified. As the Brinkman equation is employed to model the flow inside the porous medium, a too small value of the permeability means a too much penalization for the term of the Brinkman formulation in (14). To alleviate this artificial penalization, the permeability of the porous media is modified to a certain value around 1×10^{-4} for the numerical stability. It is assumed that the fluid flows towards the bottom surface in order to cool down the center domain part in Fig. 11.

Fig. 12 shows the optimal design with the present topology optimization framework. Through the topology optimization approach, a converging nozzle shape design can be obtained. By this shallow channel, the fluid can be concentrated and there is the structure just above the objective domain whose shape is similar to the shape of a drop. This auxiliary structure separates the fluid and helps fluid to flow widely. It turns out that as the heat loss should be proportional to the fluid rate passing over the structure, it is better to increase the velocity sacrificing the flow. To prove this aspect, we solve the same problem with a slow fluid velocity in Fig. 13. As shown, the wider structure can be obtained to increase the fluid velocity. This example further shows that structures tailored by structural topology optimization can enhance the heat dissipation through the latent heat loss.

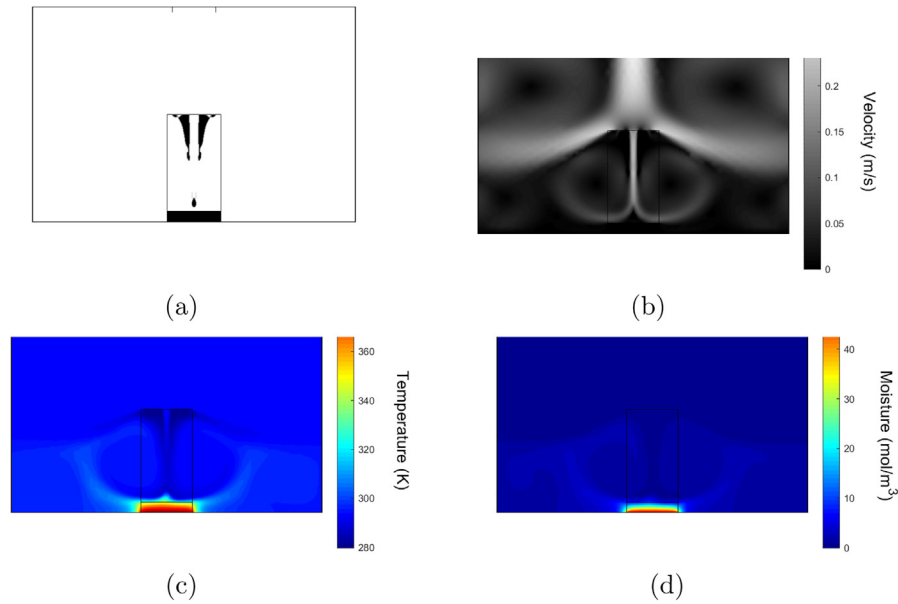


Fig. 12. Example 3 results: (a) an optimized design, (b) velocity distribution, (c) temperature distribution and (d) moisture distribution.

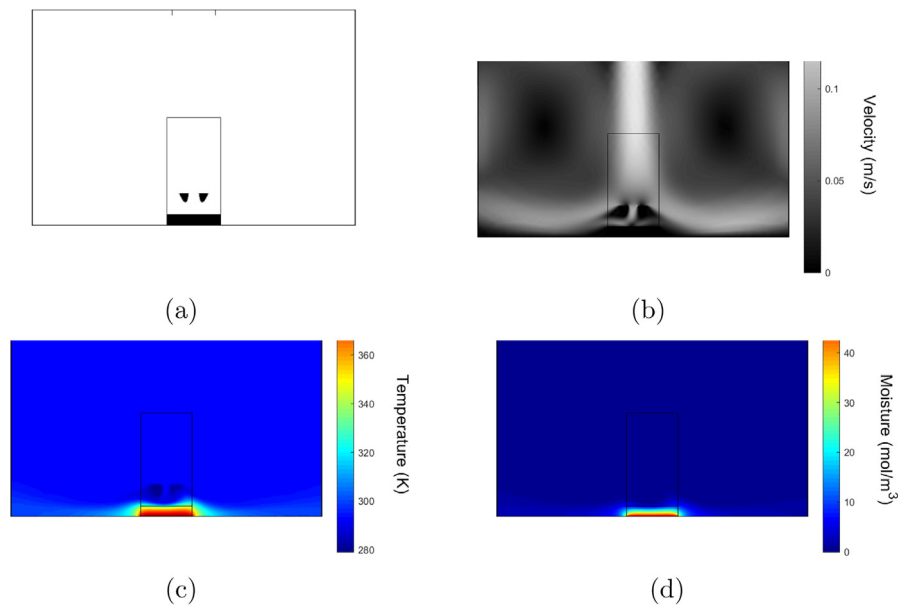


Fig. 13. An optimal design with slow fluid input: (a) an optimized design, (b) velocity distribution, (c) temperature distribution and (d) moisture distribution.

4. Conclusions

This research presents a new topology optimization method for optimal layouts considering the evaporation cooling. The evaporation cooling through the latent heat supplied or extracted by changing the state of water without modifying its temperature is one of important techniques to cool down excessive heat. To consider this evaporation process, the nonlinear multiphysics system requires a monolithic or a segregated analysis approach among Navier-Stoke equation, heat transfer equation and moisture transportation. By interpolating the involved material properties with the spatial design variables, this research presents a new topology optimization scheme for this multiphysics system. The comprehensive analysis and optimization models and frameworks developed here can simulate the mutual coupling phenomenon and

find out optimal layouts for maximizing or control latent heat loss. Several optimization problems are solved to show the validity of the present optimization scheme and the importance of the moisture transportation and the phase change. It was possible to change the flow direction and the optimal layout should be determined considering the magnitude and direction of the fluid velocity for the latent heat. For future research, we expect that the present framework can be extended to consider drying process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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