Applied Thermal Engineering 85 (2015) 89–99

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Thermal management and forced air-cooling of supercapacitors stack

Ionut Voicu [a], [*], Hasna Louahlia [a], Hamid Gualous [a], Roland Gallay [b]

[a] University of Caen Basse Normandie, LUSAC-Site de St Lô, 120 rue de l'Exode, 50000 Saint Lô, France
[b] Garmanage, Clos-Besson 6, Farvagny-le-Petit, CH-1726, Switzerland

HIGHLIGHTS

- Ventilation system for supercapacitor stack cooling is simulated.
- Cross flow staggered arrangement is considered.
- Code validation is performed in various situations proving its accuracy.
- Maximal temperatures as a function of ventilation power are compared for different pitches.
- We go further on transient regime, heat source and velocity influence for one pitch.

ARTICLE INFO

Article history:
Received 13 January 2015
Accepted 4 April 2015
Available online 14 April 2015

Keywords:
Supercapacitors stack
Thermal simulation
Staggered arrangement
Compactness
Ventilation power
Hot-spot temperature

ABSTRACT

The main objective of this study is to investigate heat transfer inside and around a supercapacitor stack. The crossflow staggered arrangement with five rows was also studied for different transverse and longitudinal pitches. The mathematical model governing the problem is numerically solved in a three-dimensional computational domain using the commercial computational fluid dynamic package Fluent 6.3. The model is elliptic and takes into account orthotropic thermal conductivity in the active zone. The average Nusselt number and friction factor results of the present model are in good agreement with previously published experimental data of different authors for flow across tube banks. The results include evolution of the maximum temperature of each supercapacitor and contours of temperature distribution. For a definite ventilation power, the arrangement with the lowest spacing provides maximum cooling performance. Inside the supercapacitor the temperature distribution is not concentric around the axis and the maximum temperature is downstream. In the axial direction the temperature variation can be neglected.

1. Introduction

Supercapacitors are electric energy storage components that provide or absorb transient power picks [1]. Their energetic and power performances are situated between those of batteries and capacitors [2]. Their available power is larger than that of batteries and smaller than that of capacitors. However, their available energy is larger than that of capacitors and smaller than that of batteries. Supercapacitors are used in applications with high power over short time to palliate the load power demand [3]. They interfere in different applications:

- Automotive, especially for the new hybrid drive system [4]
- Urban public transport like buses, tramways, and subway and long distance trains [2]
- Industrial applications such as emergency power supplies or isolated power generation systems [5]
- Household electronics including measuring devices and cameras
- Safety and storage renewable energy applications as wind turbines [6]

Component temperature is a key parameter controlling the supercapacitor efficiency [7]. The later reliability depends on the thermal and thermomechanical stresses that limit its performances [8]. Thus, a ventilation system is most of the time necessary to avoid its overheating. Cooling solution control requires extensive knowledge of the local thermal diffusion system and of the physical causes of this heat dissipation [9].

Several experimental and numerical studies have approached this problem under different configurations: a) a single supercapacitor was examined by Gualous et al. [9] with the finite difference method. Their model was bi-dimensional, where they took

---

[*] Corresponding author. Tel.: +33 2 33 77 11 73.
E-mail address: ionut.voicu@unicaen.fr (I. Voicu).

http://dx.doi.org/10.1016/j.applthermaleng.2015.04.003
1359-4311/

into account a greater thermal conductivity in the axial direction than in the radial direction. On the supercapacitor outside surface, heat transfer coefficient and air temperature were uniform at all points. b) Al Sakka et al. [8] investigated a module made of six supercapacitors for automotive applications where neighboring supercapacitors were in touch. Their numerical model was based on the analogy between the thermal and electrical phenomena to define supercapacitor temperatures. c) Hijazi et al. [4] used a staggered supercapacitor distribution with one base in contact with the airflow. Their numerical model was bi-dimensional and took into account the thermal conductivity high values in the axial direction and air temperature variation. The model used the simplifying assumptions as uniform heat transfer coefficient, constant velocities in the flow sections, and an imposed flow distribution around the supercapacitors. The experimental and numerical results were in good accordance. d) Recently, simple and accurate thermal simulation models for compact supercapacitor modules have been proposed. Frivaldsky et al. [10] used the 3D Computational Fluid Dynamic software (CFD) for solving the governing equations while taking into account its geometry and spatial thermal conductivity. Three types of supercapacitor thermal models were simulated with different geometrical and physical (number of subdomains) properties. Temperature distribution was also investigated. Precise geometry did not affect thermal distribution in the internal subdomains. This very interesting study [10] focused on the comparison of different mathematical models, but did not get into the study of different supercapacitor stack arrangements. Berrueta et al. [11] conducted a study on a cooling air flow that doesn't pass across the supercapacitor stack but at the outside of a case used for enclosing it.

Namely, none of the previous studies dealing with air flow circulation across the supercapacitor stack have considered the spatial variation of convection heat transfer around the supercapacitor. Besides, the highest temperature location may depend on the local heat transfer coefficient. In fact, several numerical studies, conducted for heat exchanger applications, focused on heat transfer around a cylinder placed perpendicular to the air flow. Giordano et al. [12] and Peyrin et al. [13] studied heat transfer around one cylinder. Harsini et al. [14] examined a wavy surface created by attached horizontal cylinders and clearly demonstrated that cooling fluid velocity fields are greater on the sides exposed to the flow than those unexposed. These differences are responsible for an important dispersion of the local convective heat transfer coefficient values on the cylinder surface [12]. If we are interested in the global heat transfer, constant convection heat transfer around the supercapacitor assumption simplifies the problem without changing the results [13]. Whereas, if we want to find the maximum temperature and its position, the previous assumption can be inappropriate because the temperature field inside the supercapacitor is certainly linked to the local heat transfer coefficients.

In the electric energy storage components area, the computation of velocities and temperature fields was conducted recently with more accuracy using CFD software for different battery arrangements. Wang [15] et al. developed three dimensional CFD models with forced air cooling for a module enclosed into a case. Rajkumar et al. [16] studied natural convection from planar heat sources in a vertical channel and the effect of channel aspect ratio and stream-wise eight ratio are reported. Very recently, Yang et al. [17] presented ventilation power requirement and the average temperature of the cells for different cells arrangements. It can be seen that a large traverse spacing causes bigger temperature rise at the same inlet flow rate but reduces the ventilation power requirement. None of these studies [15–17] presented transient regime results.

This paper is an extension to earlier works in this field. Supercapacitor stacks cooled by air flow are simulated with the CFD software Fluent 6.3. Local heat transfer and variation of conductivity in different spatial directions are considered. The temperature and cooling fluid velocity distributions inside the supercapacitor stack are determined for different air flow velocities and various stack heat power levels. Several configurations are studied in order to minimize the fan power and its energy consumption, improve heat transfer, reduce space requirement and increase the supercapacitor lifetime. Additionally, thermal transient regime is approached for one of the studied cases with the aim of giving a general idea about temperatures evolution.

2. Supercapacitor distribution section based on the flow across tube bank studies

The arrangement of supercapacitors stack has not been studied extensively yet. Basing on previous studies on heat exchangers tube banks, the distance between the neighboring supercapacitors in the stack can be chosen. In fact, the heat transfer from a tube bank in cross flow is commonly found in various industrial applications associated with evaporation or sublimation such as steam generation in boilers, refrigerators and air conditioners as presented by the Cengel and Ghajar [18] and Incropera et al. [19] books. The tube rows of the bank are either staggered or in-line on the perpendicular direction of the external fluid flow. The configuration is characterized by the tube diameter D and by the transverse pitch S_T, the longitudinal pitch S_L, and the diagonal pitch S_D measured between tube centers (Fig. 1). The fluid approaching through area A_i passes through area A_T and then through area $2A_D$ as it warps around the pipe in the next row.

The tubes affect the flow pattern and turbulence level downstream and, consequently, the heat transfer from them. Flow around tubes in the first row of tubes corresponds to one single cylinder in cross flow. However, for subsequent rows, the flow depends on the tubes arrangement. The convection heat transfer increases with the position in the increasing row number until approximately the fifth row. Above this later position there is only little change in the turbulence [19]. Flow characteristics depend on the maximum cooling fluid velocity. Reynolds number is defined as a function of the maximum fluid velocity. The outer tube diameter D is taken as the characteristic length.

$$Re_D = \rho v_{max} D/\mu = v_{max} D/\nu \tag{1}$$

Khan et al. [20] and Safwat et al. [21] studied in-line and staggered tubes arrangements for heat exchangers and concluded that:

- The average heat transfer coefficients for tube banks depend on the longitudinal and transverse pitches, Reynold and Prandtl numbers.
- The compact banks have higher heat transfer rates than widely spaced ones
- The staggered arrangement has a higher heat transfer than the in-line one especially in low range of S_L/D.

Consequently in the present study the staggered configuration with compact banks has been chosen for supercapacitor stacks in order to improve heat transfer. Anyway the compactness of the supercapacitor bank is an important criterion especially for the design of transport applications.

Several correlations of average Nusselt numbers based on experimental data, for cross flow over staggered tube banks, are proposed in literature [18–20]. Incropera et al. [19] presented a