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VISUALIZATION OF INDUCED COUNTER-ROTATING VORTICES FOR ELECTRIC VEHICLES BATTERY MODULE THERMAL MANAGEMENT

A.C. Budiman[a,*] S. M. Hasheminejad[b], Sudirja[a], A. Mitayani[c], S. H. Winoto[d]

[a] *Research Centre for Electrical Power and Mechatronics, National Research and Innovation Agency (BRIN). Kompleks BRIN, Jl. Sangkuriang 10, Bandung, Jawa Barat 40135, Indonesia.*
[b] *Iran University of Science and Technology, Tehran, 13114-16846, Iran.*
[c] *Research Centre for Electronics and Telecommunication, National Research and Innovation Agency (BRIN). Kompleks BRIN, Jl. Sangkuriang 10, Bandung, Jawa Barat 40135, Indonesia.*
[d] *formerly at Dept. of Mechanical Engineering, National University of Singapore. 9 Engineering Drive 1, Singapore 117575, Singapore.*

ABSTRACT

Streamwise development of counter-rotating vortices induced by three different types of chevron Vortex Generators (VGs) placed upstream an Electric Vehicles (EV) dummy battery module is experimentally visualized using a smoke-wire method. From the single chevron reference case, the mushroom-like vortices do not collapse until passing the module. When more chevrons are used in line, the vortices become more prominent. It can also be observed that the vortex sizes and shapes are significantly influenced by the spanwise base length of the chevron. The induced vortices from all three VGs suggest a potential heat transfer augmentation for the EV battery module application.

Keywords: Streamwise vortices; Boundary-layer flow; Vortex Generator; Smoke-wire flow visualization.

1. INTRODUCTION

Electric Vehicles (EVs) have been massively developed besides sustainable resources of energy in recent years due to the increasing demand to reduce the global dependency on fossil fuels and their environmental impact (Guerra, 2019; Ismaeel *et al.*, 2020; Pisarov and Mester, 2021). Most EVs in the market rely on Lithium-based batteries with proper battery thermal management in order to maintain their peak performance. Such battery requires a stable temperature profile of preferably between 25 to 30^{o}C and should be no more than 40^{o}C, otherwise its efficiency would drop dramatically (Arora, 2018; Arora *et al.*, 2018). Without proper thermal protection, the cell temperature may continually increase until the so-called thermal runaway condition, which is hazardous for EV (Feng *et al.*, 2018; Smith and Wang, 2006). It is also worth noting that a battery pack or module in an EV usually consists of many battery cells arranged tightly to save space and weight, hence the thermal management issue becomes more complex.

Various EV thermal management systems can generally be classified into three categories based on the fluid and heat transfer mechanism, that is, passive, active, and hybrid active-passive methods (Ianniciello *et al.*, 2017; Kim *et al.*, 2019). The passive system relies solely on thermodynamics without any electrical power requirement, such as using a heat sink or Phase Change Materials (Amin *et al.*, 2018; Budiman *et al.*, 2020, 2022; Chen *et al.*, 2014). Such a passive system is considerably more straightforward and economical in its design. On the other hand, the active system uses a fan or pump in order to enforce the heat dissipation from the battery surface to the air, water, or other cooling fluids. Among the cooling fluids, air is one of the conventional methods still popular to date. An air cooling system would not need any storage; hence the overall vehicle weight could be saved. Despite its simplicity, the air has low thermal conductivity and heat capacity to produce a highly efficient thermal management system for an extended period of operations or harsh environments (Fan *et al.*, 2013; Talluri *et al.*, 2020; Ye *et al.*, 2019). Therefore, any attempts to improve the heat transfer for an air cooling system, such as the utilization of vortex flow instability, would certainly be interesting.

A fluid flow instability mechanism in the form of counter-rotating streamwise vortices has been known for its potential to improve the overall heat and mass transfer in the industrial applications (Chamoli *et al.*, 2017; Cheng *et al.*, 2020; Girgis and Liu, 2002; Moradi *et al.*, 2017). Naturally developed counter-rotating vortices could be found in various conditions, such as Görtler vortices due to the curvature of the concave surface, Dean vortices in fully developed flow in curved pipes and curved rectangular cross-section ducts, as well as in flow between concentric cylinders and rough surfaces. However, the evolution of such vortices is relatively challenging to analyze as they appear in various sizes and growth rates (Aider *et al.*, 2008; Budiman *et al.*, 2016). On the other hand, the use of perturbation wires, modifications on the leading edge (Hasheminejad *et al.*, 2016), artificial surface roughness (Hayakawa *et al.*, 2022), plasma actuators (Shadmani *et al.*, 2018), or a robust yet economical device called Vortex Generator (VG) (Samadifar and Toghraie, 2018) is practical in studying the evolution of vortices and their effects in enhancing mass and heat transfer.

Previous evaluations on the effect of VG in channel flow reported a significant increase in terms of local heat transfer augmentation (Fiebig *et al.*, 1991; Lei *et al.*, 2017; Lertnuwat, 2022; Rajesh Kanna *et al.*, 2017; Xu *et al.*, 2017). In other engineering applications, VG is used to delay the flow separation hence the aerodynamic drag reduction in turbulence flow (Gao *et al.*, 2020; Kasai *et al.*, 2018; Lo and Kontis, 2016; Patil *et al.*, 2021; Zhao *et al.*, 2017) and improvement in terms of vehicle stability during the cruise (Katz, 2006). Various designs have

* *Corresponding author; Email: alex003@brin.go.id*

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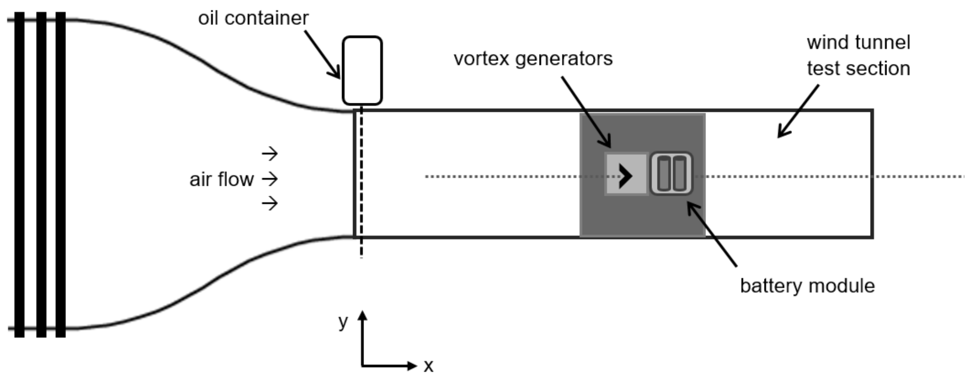

Fig. 1 Sketch of the wind tunnel flow visualization setup as seen from the camera-side (not to scale) with the VG and battery module inside the test section.

been developed with their respective unique advantages and disadvantages reported. It is also worth noting that careful calculations and observations are required in designing the VG to prevent any adverse problems. For example, an improper vortex flow might cause the cooling fluid not to be well distributed or increase pressure losses, hence reducing its effectiveness (Song *et al.*, 2019). Therefore, a qualitative observation, such as using smoke-wire flow visualization, is of practical importance especially due to the invisibility of air. It would be helpful to see an induced vortex in motion so that its growth and evolution could be further examined.

In this study, the induced counter-rotating streamwise vortices on a flat plate upstream of the dummy battery module are experimentally visualized and analyzed. The presence of a battery cell/module downstream of the Vortex Generators (VG) creates an adverse pressure gradient, which affects the development of the vortices compared to that on a flat plate. The comparisons between the images captured at different locations for three different VG designs are carefully analyzed in this work. If the induced vortices on the battery module could still be detected, it could lead to an improvement of the heat dissipation from the battery surface during discharge.

2. EXPERIMENTAL SETUP

The experimental rig is shown in Fig. 1. The Vortex Generator is made by means of 3D printing using Polylactic Acid (PLA) filaments. Three variations of VG are sketched in Fig. 2. The base design has a chevron shape with base length $\lambda = 10$ mm, 60° tip angle, 2 mm thickness, and 3 mm height, as shown in Fig. 2(a). The other two designs consist of triple chevrons placed in a single line along the flow direction. The third design, code-named and described as triple chevrons with extended edges, was made by increasing the length so that all the three chevrons originated from the same spanwise line hence the maximum spanwise length $\lambda_e = 26$ mm. Each VG, as well as the battery module replica used in this study, are mounted on a flat plate and inserted into a wind tunnel test section, which has a square cross-sectional area of 400 mm x 400 mm. To avoid flow separation, a fillet was carved on the leading edge of the flat plate.

The streamwise distance between the leading edge and the VG base is 180 mm, which is 10 D, where D is the diameter of the 18650 battery cell used to construct the battery module. On the other hand, the battery module is placed at 5 D downstream of the VG base. During this flow visualization experiment, the battery module was detached from any electrical circuits and all the cables were removed. The room temperature throughout the experiment was about 27°C. The free stream velocity $U_\infty = 1.6 \pm 0.1$ m/s, giving the Re approximately 20000. In terms of the VG base length λ, the corresponding $Re_\lambda = 1095$ and 2847 for the base VG and the extended edge, respectively. The wind tunnel turbulence intensity $Tu < 0.4\%$ for such velocity.

The smoke-wire visualization setup consists of a thin, electrically heated Nickel-Chromium wire and a pressurized white oil container. A continuous smoke layer is produced as the oil drips along the heated wire. The setup is placed upstream of the flat plate in the wind tunnel test section. The traversing mechanism allows users to adjust the position of the smoke-wire in the spanwise direction. A 12 MP digital camera is used to capture the still images and record the videos from outside of the transparent test section. A 50 W, 532 nm green laser pointer is connected to a glass cylinder to create a laser sheet to illuminate the flowing smoke.

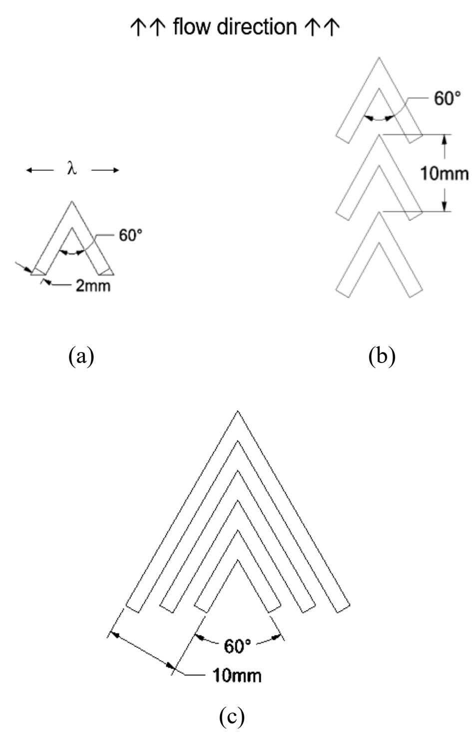

Fig. 2 Vortex Generator designs used in this work: a) base, single chevron; b) triple chevrons, and c) triple chevrons with extended edges.

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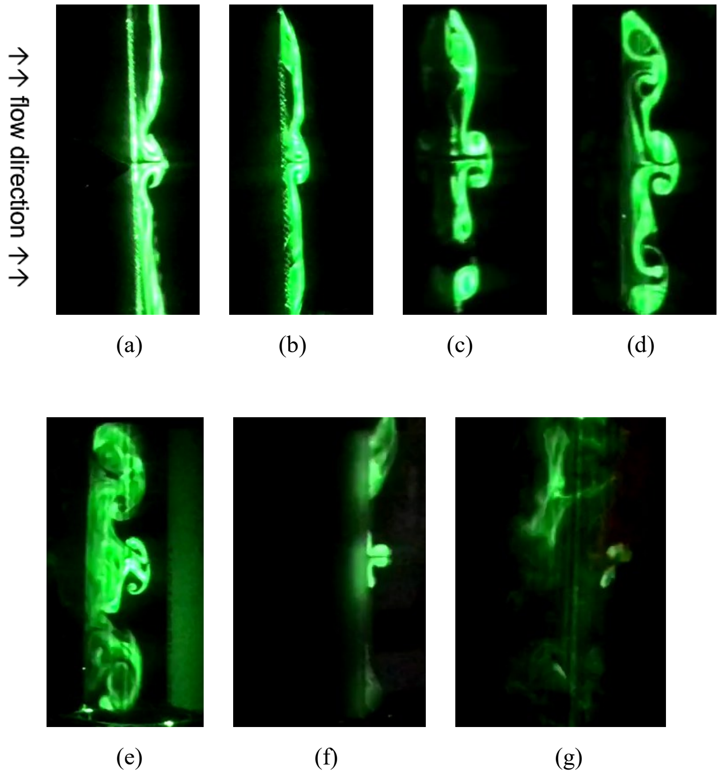


Fig. 3 Downstream development of counter-rotating vortices induced by a single chevron VG shown in Fig. 2(a), as captured at: (a) end tip of the VG, (b) 4 D, (c) 3 D, (d) 2 D, (e) 1 D upstream the battery module; (f) on top of the module, and (g) downstream the module.

3. RESULTS AND DISCUSSION

The chevron shape Vortex Generators (VG) is known to effectively induce counter-rotating streamwise vortices in a unique mushroom-like shape. In line with the sharp end of the VG, the boundary-layer would be thicker due to the uplift momentum experienced by the fluid, creating the so-called upwash. Following the continuity principle, another region called downwash would be formed, indicated by a significantly thinner boundary-layer (Méndez *et al.*, 2020; Tandiono *et al.*, 2009; Winoto *et al.*, 2015).

Figure 3 shows the downstream development of the counter-rotating vortices induced by the base chevron (Fig. 2(a)). It can be observed that the spanwise boundary-layer thickness changes due to the presence of such vortices. In the beginning, such mushroom-like structures would generally be attached to the surface until their breakdown to turbulence. This result is also in agreement with (Budiman *et al.*, 2013; Singh, 2019). As it travels downstream and closer to the battery module, the mushroom stem grows longer resulting in a slightly lifted up structure from the surface. The growth of such stem is an early indication that the vortices would breakdown soon (Winoto *et al.*, 2015). A separation bubble starts to form beneath the mushroom, leading to the formation of the other mushroom-like structures found on each side of the induced vortices. At approximately 2 D distance before reaching the battery, the vortices are lifted further and become less distinct, as depicted in Fig. 3(d). In Fig. 3(e), the battery module can be seen in green behind the vortices. Flowing over the module, the counter-rotating vortices could still be visible on top of it (Fig. 3(f)). Finally, the structure became significantly more blur due to the mixing augmentation after the vortices had passed the module, even though the pair of rotational movements could still be observed, as seen in Fig. 3(g). Overall the structures could be seen notably further downstream compared to the case of induced vortices on a flat plate, where the vortices break to

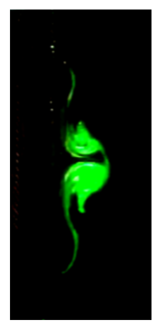


Fig. 4 Streamwise counter-rotating vortices generated by the triple chevrons VG (λ = 10 mm) at the 2 D upstream the battery module.

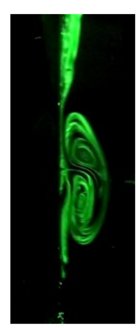
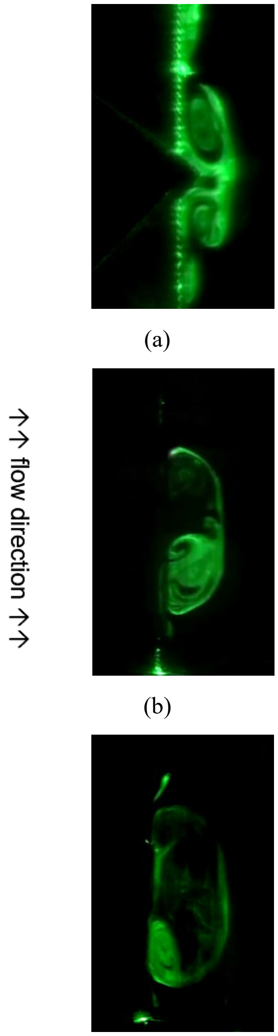


Fig. 5 Streamwise counter-rotating vortices generated by the triple chevrons with extended edges VG (λ_e = 26 mm) at the 2 D upstream the battery module.



(a)

(b)

(c)

Fig. 6 Downstream development of counter-rotating vortices induced by triple chevrons with extended edges VG as in Fig. 2c, as captured at: (a) end tip of the VG, (b) 2 D, and (c) 1 D upstream the battery module.

turbulence no more than 2 D distance from the leading edge (Hasheminejad *et al.*, 2016).

A side-by-side comparison at the exact location is made and presented in Figs. 4 and 5 for the other two VG designs. The triple chevrons design, made from arranging three identical VG in a line, creates relatively stronger counter-rotating vortices, as indicated by a more prominent mushroom-like structure in Fig. 4. The mushroom hat is slightly bigger with a tiny, almost invisible mushroom stem. Furthermore, as compared to Fig. 3(d), the structure is still attached to the surface, which indicates that the structure is relatively more stable and firm. This could lead to a potentially better heat dissipation from the battery, if the structure could be well presered when flowing over the module. It can also be noted that the mushroom-like structure seems to have a similar spanwise width/size with the base design. In contrast, in the extended edge case, it can be seen from Fig. 5 that the induced streamwise counter-rotating vortices have a significantly different shape and size. Subsequently, Fig. 6 presents the development of such vortices as seen at the tip of the VG and two further downstream locations. It can be easily noticed that the spanwise width of the structures is dramatically increased, as it is significantly affected by the spanwise distance of the VG base. The overall shape of the vortices suggests that the structure is more stable than a single chevron.

4. CONCLUSION

Counter-rotating streamwise vortices induced by three different chevron Vortex Generators designs have been experimentally observed and analyzed using the smoke-wire flow visualization method. The Vortex Generators were mounted on a flat plate upstream of an Electric Vehicles battery module replica in order to observe the downstream development of such vortices in the presence of such a module. From a single chevron as the base reference, the induced vortices can be seen in the form of mushroom-like structures attached to the surface. As it flows downstream and closer to the battery, the mushroom stem becomes more prominent, a thin separation bubble is developed, and two other vortices are formed at each side. The main structure remains visible until it passes the module. On the other hand, when three identical chevrons are placed in the streamwise direction, the induced vortices are relatively more prominent. Finally, by arranging three identical VGs in a streamwise direction, the counter-rotating vortices have a bigger spanwise size and perhaps stronger circulations as they remain attached to the surface. Both the three chevrons could lead to more mixing and heat transfer enhancement than a single VG used.

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NOMENCLATURE

D	distance based on the diameter of the 18650 battery cell (18 mm)
Re	Reynolds number
Re_λ	Reynolds number based on λ
Tu	wind tunnel turbulence intensity
U_∞	free stream velocity

Greek symbols

λ	base length of the vortex generator
λ_e	maximum spanwise base length

REFERENCES

Aider, J.-L., Duriez, T., and Wesfreid, J.E., 2008, "From natural to forced counter-rotating streamwise vortices in boundary layers," *Journal of Physics: Conference Series*, **137**, 012009. https://dx.doi.org/10.1088/1742-6596/137/1/012009

Amin, M., Ariantara, B., Putra, N., Sandi, A.F., and Abdullah, N.A., 2018, "Thermal Management of Electric Vehicle Batteries Using Heat Pipe and Phase Change Materials," E. Kusrini, F. H. Juwono, A. Yatim, and E. A. Setiawan, eds., *The 3rd International Tropical Renewable Energy Conference "Sustainable Development of Tropical Renewable Energy" (i-TREC 2018)*, EDP Sciences, **67**, 03034. https://dx.doi.org/10.1051/e3sconf/20186703034

Arora, S., 2018, "Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging

technologies," *Journal of Power Sources*, **400**, 621–640.
https://dx.doi.org/10.1016/j.jpowsour.2018.08.020

Arora, S., Kapoor, A., and Shen, W., 2018, "Application of Robust Design Methodology to Battery Packs for Electric Vehicles: Identification of Critical Technical Requirements for Modular Architecture," *Batteries*, **4**(3), 30.
https://dx.doi.org/10.3390/batteries4030030

Budiman, A.C., Kaleg, S., Amin, Sudirja, and Hapid, A., 2020, "Experimental Investigation of Phase Change Materials Thermal Barriers in Electric Vehicle Battery Module," *2020 International Conference on Sustainable Energy Engineering and Application (ICSEEA)*, 30–34.
https://dx.doi.org/10.1109/ICSEEA50711.2020.9306136

Budiman, A.C., Kaleg, S., Sudirja, Amin, and Hapid, A., 2022, "Passive thermal management of battery module using paraffin-filled tubes: An experimental investigation," *Engineering Science and Technology, an International Journal*, **29**, 101031.
https://dx.doi.org/10.1016/j.jestch.2021.06.011

Budiman, A.C., Mitsudharmadi, H., Bouremel, Y., Winoto, S.H., and Low, H.T., 2016, "Effects of Wavy Channel Entrance Design on Streamwise Counter-rotating Vortices: a Visualization Study," *Journal of Applied Fluid Mechanics*, **9**(7), 2161–2166.
https://dx.doi.org/10.18869/acadpub.jafm.68.236.25657

Budiman, A.C., Mitsudharmadi, H., Low, H.T., and Winoto, S.H., 2013, "Visualization of Counter-rotating Streamwise Vortices in a Rectangular Channel with One-sided Wavy Surface," *the 31st AIAA Applied Aerodynamics Conference*, AIAA 2013-2533.
https://dx.doi.org/10.2514/6.2013-2533

Chamoli, S., Lu, R., and Yu, P., 2017, "Thermal characteristic of a turbulent flow through a circular tube fitted with perforated vortex generator inserts," *Applied Thermal Engineering*, **121**, 1117–1134.
https://dx.doi.org/10.1016/j.applthermaleng.2017.03.145

Chen, J., Yang, D., Jiang, J., Ma, A., and Song, D., 2014, "Research Progress of Phase Change Materials (PCMs) Embedded with Metal Foam (a Review)," *Procedia Materials Science*, **4**, 389–394.
https://dx.doi.org/10.1016/j.mspro.2014.07.579

Cheng, K.X., Foo, Z.H., and Ooi, K.T., 2020, "Heat transfer enhancement through periodic flow area variations in microchannels," *International Communications in Heat and Mass Transfer*, **111**, 104456.
https://dx.doi.org/10.1016/j.icheatmasstransfer.2019.104456

Fan, L., Khodadadi, J.M., and Pesaran, A.A., 2013, "A parametric study on thermal management of an air-cooled lithium-ion battery module for plug-in hybrid electric vehicles," *Journal of Power Sources*, **238**, 301–312.
https://dx.doi.org/10.1016/J.JPOWSOUR.2013.03.050

Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., and He, X., 2018, "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review," *Energy Storage Materials*, **10**(December 2016), 246–267.
https://dx.doi.org/10.1016/j.ensm.2017.05.013

Fiebig, M., Kallweit, P., Mitra, N., and Tiggelbeck, S., 1991, "Heat transfer enhancement and drag by longitudinal vortex generators in channel flow," *Experimental Thermal and Fluid Science*, **4**(1), 103–114.
https://dx.doi.org/10.1016/0894-1777(91)90024-L

Gao, W., Chen, J., Liu, C., Li, Z., Yang, J., and Zeng, Y., 2020, "Effects of vortex generators on unsteady unstarted flows of an axisymmetric inlet with nose bluntness," *Aerospace Science and Technology*, **104**, 106021.
https://dx.doi.org/10.1016/j.ast.2020.106021

Girgis, I.G., and Liu, J.T.C., 2002, "Mixing enhancement via the release of strongly nonlinear longitudinal Görtler vortices and their secondary instabilities into the mixing region," *Journal of Fluid Mechanics*, **468**, 29–75.
https://dx.doi.org/10.1017/S0022112002001519

Guerra, E., 2019, "Electric vehicles, air pollution, and the motorcycle city: A stated preference survey of consumers' willingness to adopt electric motorcycles in Solo, Indonesia," *Transportation Research Part D: Transport and Environment*, **68**, 52–64.
https://dx.doi.org/10.1016/J.TRD.2017.07.027

Hasheminejad, S.M., Mitsudharmadi, H., Winoto, S.H., Lua, K.B., and Low, H.T., 2016, "Streamwise counter-rotating vortices generated by triangular leading edge pattern in flat plate boundary layer," *Journal of Visualization*, **19**(3), 359–367.
https://dx.doi.org/10.1007/s12650-015-0333-7

Hayakawa, S., Fukue, T., Sugimoto, Y., Hiratsuka, W., Shirakawa, H., and Koito, Y., 2022, "Effect of Rib Height on Heat Transfer Enhancement By Combination of a Rib and Pulsating Flow," *Frontiers in Heat and Mass Transfer*, **18**.
https://dx.doi.org/10.5098/hmt.18.29

Ianniciello, L., Biwole, P.H., and Achard, P., 2017, "A hybrid system for battery thermal management for electric vehicles," *European Battery, Hybrid and Fuel Cell Electric Vehicle Congress*, 1–7.

Ismaeel, T.A., Aljabair, S., Abdulrazzaq, O.A., and Abood, Y.A., 2020, "Energy recovery of moving vehicles' wakes in highways by vertical axis wind turbines," *FME Transactions*, **48**(3), 557–565.
https://dx.doi.org/10.5937/fme2003557I

Kasai, A., Shiratori, S., Kohri, I., Kobayashi, Y., Katoh, D., Nagano, H., and Shimano, K., 2018, "Large-Scale Separated Vortex Generated in a Wake Flow of Ahmed's Body," *Flow, Turbulence and Combustion*, 1–16.
https://dx.doi.org/10.1007/s10494-018-9950-2

Katz, J., 2006, "Aerodynamics of Race Cars," *Annual Review of Fluid Mechanics*, **38**(1), 27–63.
https://dx.doi.org/10.1146/annurev.fluid.38.050304.092016

Kim, J., Oh, J., and Lee, H., 2019, "Review on battery thermal management system for electric vehicles," *Applied Thermal Engineering*, **149**, 192–212.
https://dx.doi.org/10.1016/j.applthermaleng.2018.12.020

Lei, Y., Zheng, F., Song, C., and Lyu, Y., 2017, "Improving the thermal hydraulic performance of a circular tube by using punched delta-winglet vortex generators," *International Journal of Heat and Mass Transfer*, **111**, 299–311.
https://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.101

Lertnuwat, B., 2022, "the Effects of Winglet Vortex Generator Position in Rectangular-Duct-Type Solar Air Heaters," *Frontiers in Heat and Mass Transfer*, **18**(1), 1–9.
https://dx.doi.org/10.5098/hmt.18.1

Lo, K.H., and Kontis, K., 2016, "Flow characteristics over a tractor-trailer model with and without vane-type vortex generator installed," *Journal of Wind Engineering and Industrial Aerodynamics*, **159**, 110–122.
https://dx.doi.org/10.1016/J.JWEIA.2016.10.009

Méndez, M., Shadloo, M.S., and Hadjadj, A., 2020, "Heat-transfer analysis of a transitional boundary layer over a concave surface with Görtler vortices by means of direct numerical simulations," *Physics of Fluids*, **32**, 074111.
https://dx.doi.org/10.1063/5.0015503

Moradi, H. V., Budiman, A.C., and Floryan, J.M., 2017, "Use of natural instabilities for generation of streamwise vortices in a laminar channel flow," *Theoretical and Computational Fluid Dynamics*, **31**(3), 233–250.
https://dx.doi.org/10.1007/s00162-016-0418-5

Patil, M., Gawade, R., Potdar, S., Nadaf, K., Suresh, S.P., and Sahoo, D., 2021, "Effect of Vortex Generator on the Flow Field over a Conventional Delta Wing in Subsonic Flow Condition at Higher Angles of Attack," *FME Transactions*, **49**(2), 395–400.
https://dx.doi.org/10.5937/fme2102395P

Pisarov, J., and Mester, G., 2021, "The future of autonomous vehicles," *FME Transactions*, **49**(1), 29–35.
https://dx.doi.org/10.5937/fme2101029p

Rajesh Kanna, P., Sivasubramanian, M., and Uthayakumar, M., 2017, "Numerical investigation of forced convection heat transfer from square cylinders in a channel covered by solid wall - Conjugate situation," *FME Transactions*, **45**(1), 16–25.
https://dx.doi.org/10.5937/fmet1701016K

Samadifar, M., and Toghraie, D., 2018, "Numerical simulation of heat transfer enhancement in a plate- fin heat exchanger using a new type of vortex generators," *Applied Thermal Engineering*, **133**, 671–681.
https://dx.doi.org/10.1016/j.applthermaleng.2018.01.062

Shadmani, S., Nainiyan, S.M.M., Mirzaei, M., Ghasemiasl, R., and Pouryoussefi, S.G., 2018, "Experimental Investigation of Flow Control over an Ahmed Body using DBD Plasma Actuator," *Journal of Applied Fluid Mechanics*, **11**(5), 1267–1276.
https://dx.doi.org/10.29252/jafm.11.05

Singh, N.K., 2019, "Numerical Simulation of Flow behind Vortex Generators," *Journal of Applied Fluid Mechanics*, **12**(4), 1047–1061.
https://dx.doi.org/10.29252/jafm.12.04.29330

Smith, K., and Wang, C.-Y., 2006, "Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles," *Journal of Power Sources*, **160**(1), 662–673.
https://dx.doi.org/10.1016/J.jpowsour.2006.01.038

Song, K., Tagawa, T., Chen, Z., and Zhang, Q., 2019, "Heat transfer characteristics of concave and convex curved vortex generators in the channel of plate heat exchanger under laminar flow," *International Journal of Thermal Sciences*, **137**, 215–228.
https://dx.doi.org/10.1016/j.ijthermalsci.2018.11.002

Talluri, T., Kim, T.H., and Shin, K.J., 2020, "Analysis of a battery pack with a phase change material for the extreme temperature conditions of an electrical vehicle," *Energies*, **13**(3).
https://dx.doi.org/10.3390/en13030507

Tandiono, T., Winoto, S.H., and Shah, D.A., 2009, "Wall shear stress in Görtler vortex boundary layer flow," *Physics of Fluids*, **21**(8), 1–9.
https://dx.doi.org/10.1063/1.3205428

Winoto, S.H., Mitsudharmadi, H., Budiman, A.C., Hasheminejad, S.M., Nadesan, T., Tandiono, Low, H.T., and Lee, T.S., 2015, "On generating counter-rotating streamwise vortices," *IOP Conference Series: Materials Science and Engineering*, **88**, 012001.
https://dx.doi.org/10.1088/1757-899X/88/1/012001

Xu, Y., Islam, M.D., and Kharoua, N., 2017, "Numerical study of winglets vortex generator effects on thermal performance in a circular pipe," *International Journal of Thermal Sciences*, **112**, 304–317.
https://dx.doi.org/10.1016/j.ijthermalsci.2016.10.015

Ye, B., Rubel, M.R.H., and Li, H., 2019, "Design and Optimization of Cooling Plate for Battery Module of an Electric Vehicle," *Applied Sciences*, **9**(4), 754.
https://dx.doi.org/10.3390/app9040754

Zhao, Z., Shen, W., Wang, R., Wang, T., Xu, B., Zheng, Y., and Qian, S., 2017, "Modeling of wind turbine vortex generators in considering the inter-effects between arrays," *Journal of Renewable and Sustainable Energy*, **9**(5), 053301.
https://dx.doi.org/10.1063/1.4997039