Mathematical modeling and numerical simulation of thermoelectric generator

Cite as: AIP Conference Proceedings **2274**, 030037 (2020); https://doi.org/10.1063/5.0022427
Published Online: 05 October 2020

R. S. Kondaguli, and P. V. Malaji

Mathematical Modeling and Numerical Simulation of Thermoelectric Generator

R.S. Kondaguli[a)] and P.V. Malaji

Department of Mechanical Enineering, B.L.D.E A's V.P Dr. P G Halakatti College of Engineering. & Technology, Vijayapura – 586103, INDIA

Corresponding Author: [a)]ravindrakondaguli@gmail.com

ABSTRACT

As demand for energy is increasing, there is need of harvesting energy from waste energy. Thermal energy is low grade energy, heat engines can convert only about 35% of available energy the rest is waste heat. This waste heat can be converted into useful energy by thermoelectric generator. A thermoelectric device consist of a P-Type and N-type semiconductor connected electrically in series and thermally in parallel and it works on Seebeck principle. Thermoelectric generator directly converts thermal energy to electrical energy without any moving parts, they are light weight potentially they are less prone to failure because no moving parts are involved. Presently the use of thermoelectric devices is limited because of low efficiencies they work on about 10% of Carnot efficiency. Efficiency of a thermoelctric generator can by improving ZT value of materials and design of thermoelectric generator. The present work develops zero dimensional analytical models & analyzed. Later a 3D model of the same was numerically simulated using ANSYS workbench. Insights of numerical model are discussed such as variation of power with variation load, length of leg.

Keywords: Thermoelectric Materials, TEG, Simulation, Modeling

INTRODUCTION

Energy is one of the major inputs for the economic development of any country. In developing countries like India, Energy sector is of critical importance. Thermal energy is extracted from non-renewable Sources as non-renewable source of energy are likely to deplete with time. It is extremely important to utilize non-renewable resources in appropriate manner. Thermal energy is low grade energy and hence we cannot convert the entire available energy to use full form of work. Internal combustion engines are the most important and viable method of utilizing thermal energy but the efficiency of IC engine is about 40 % means the rest of the thermal energy or heat is lost in the form of waste heat. Indian automobile industry is fastest growing sector for the last few decades. India's annual production is 29 Million vehicles in the financial year 2018. Compared to 22 million in the financial year 2017, population of automobiles in India is expected to Surge to 404 million by 2028 [11]. This means a large amount of heat is being lost by automobiles vehicles, if only a part of waste heat is recovered from each vehicle cumulatively it will cause big impact. It will increase efficiency of automobile vehicle there are devices like thermoelectric generator that can convert this waste heat to useful energy. Thermoelectric generators are the solid state devices that convert waste heat directly to electrical energy. It is expected that market of thermoelectric materials to reach 78.8 million dollars by 2023 [2]. Now TE devices are used mainly if efficiency is not a major issue. Till today efficiency of Carnot efficiency is taken as maximum limit for TE devices [3]. Presently TE devices are limited by their low efficiency; presently TE devices operate nearly about 10% of Carnot efficiency. Thermoelectric generator works on Seebeck principle.

Proceedings of International Conference on Advances in Materials Research (ICAMR - 2019)
AIP Conf. Proc. 2274, 030037-1–030037-7; https://doi.org/10.1063/5.0022427
Published by AIP Publishing. 978-0-7354-4004-3/$30.00

A TE device contains several pairs of thermoelectric element (P-N pair) which are connected electrically in series and thermally in parallel. Performance of TE device is related by term called figure of merit $ZT = \frac{\alpha^2}{\rho k}T$ in above equation α is Seebeck coefficient. T is temperature; k thermal conductivity of the material, ρ is electrical resistivity of the material. A good thermoelectrical material should have high Seebeck coefficient, high electrical conductivity and low thermal conductivity [4-5]. Previously it was observed that all good thermal conducting materials are good electrical materials and ZT value was limited to 1 [11]. Loffe was the first to promote the use of alloying to reduce Lattice thermal conductivity by point defects. Segmented and asymmetric thermoelectric generator was analyzed using COSMOL and reported that power developed is increased by 117 % compared to conventional thermoelectric generator [12]. TEG Analysis by numerical and experimental methods using temperature dependent thermoelectric generator properties for different configuration of heat exchanger, reported that maximum power output is obtained at ratios of load resistance to internal resistance of about 1.5 to 1.7 [13]. Analysis of segmented models in an exhaust based thermoelectric generator for waste heat recovery in segmented thermoelectric generator showed there is increase of 13% of maximum power compared to conventional thermoelectric generator [14]. Traditional thermoelectric generator are compared with porous thermoelectric generator for waste heat harvesting, power output increased to peak values and then decreases with increase in porosity external electrical resistance and cross section area of the TEG[15]. A mathematical Modeling and analysis is done by considering Seebeck effect, Thomson effect and compared result with FEA models [16].

Heavily doped semiconductors are good thermoelectric materials. TEG can be mathematically as zero dimensional, 1D, 2D and 3D models. Zero dimensional models includes formulation of algebraic equations at source and sink without considering any differential equations [6].

Single Pair Thermoelectric Module

The performance of TEG is analyzed and we assume that no heat arrives at the sink other than the two branches. R_L is the load resistance

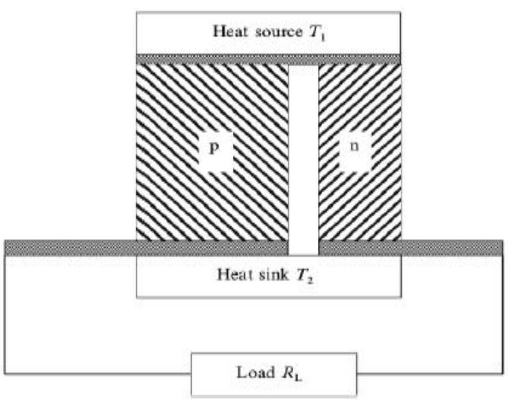

FIGURE 1. Thermoelectric module

Governing equations:

if T_h is source temperature

if T_L is sink temperature

1)Current $I = \frac{(\alpha P - \alpha N)(Th - TL)}{Rp + Rn + RL}$

2)Power $= I^2R_L$

If Q_h is heat supplied to source

$Qh=\alpha_p IT_h - \frac{I2Rp}{2} + k(T_h - T_L)$

If Q_c is the heat rejected at the sink

$Qc=\alpha_n IT_L - \frac{I2Rp}{2} + k(T_h - T_L)$

Power is calculated as

$P = Q_h - Q_c$

Simulation of Thermoelectric generator using ANSYS:

Following steps are involved in simulation

1) 3D model of TEG is prepared using ANSYS Design Modeler.
2) Material data input
3) Meshing of model using ANSYS mesh
4) Providing boundary condition
5) Solving.

Modeling:

The geometry is modeled in ANSYS Design modeler. The properties of the materials and dimensions used in the simulation are as below.

Geometry	Value	Units
P type • Thermal Cross section area • Length • Seebeck coefficient • Electrical resistivity	• 2mm*2mm • varies from 0.1mm to 1.7mm • 160 • 1.27e-5	• mm^2 • mm • µV/C • Ohm m
N type • Thermal Cross section area • Length • Seebeck coefficient • Electrical resistivity	• 2mm*2mm • varies from 0.1mm to 1.7mm • -160 • 1.27e-5	• mm^2 • mm • µV/C • Ohm m
Load Resistance • Cross section area • Electrical resistivity • Electrical length	• 0.1mm*2mm • varies accordingly • 19mm	• Mm^2 • mm

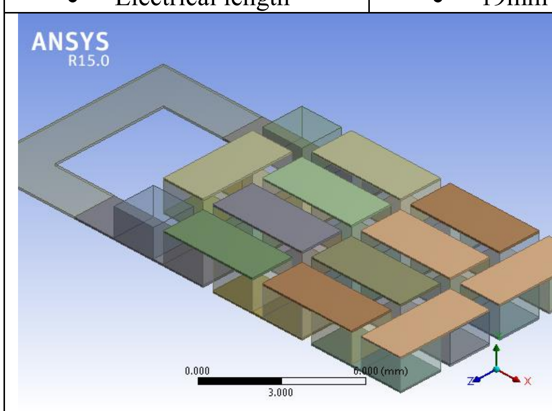

FIGURE 2. 3D Model of 12 pairs TEG

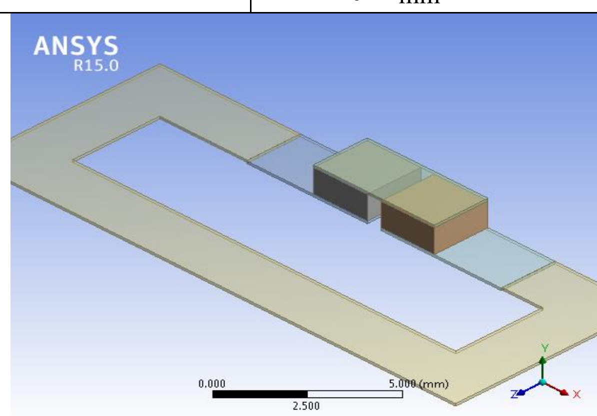

FIGURE 3. Single pair TEG module

The above figure shows 3D model of TEG prepared using ANSYS design modeler. The present module consists of 12pairs of thermocouples each pair contains P type, N-type semiconductor and electrical copper conductor. The numerical study is done by varying load resistance and varying leg length. Material properties are assigned to each part in thermal electrical model.

Meshing:

Meshing is important step of simulation accuracy of results depends on meshing. The following are meshing details.

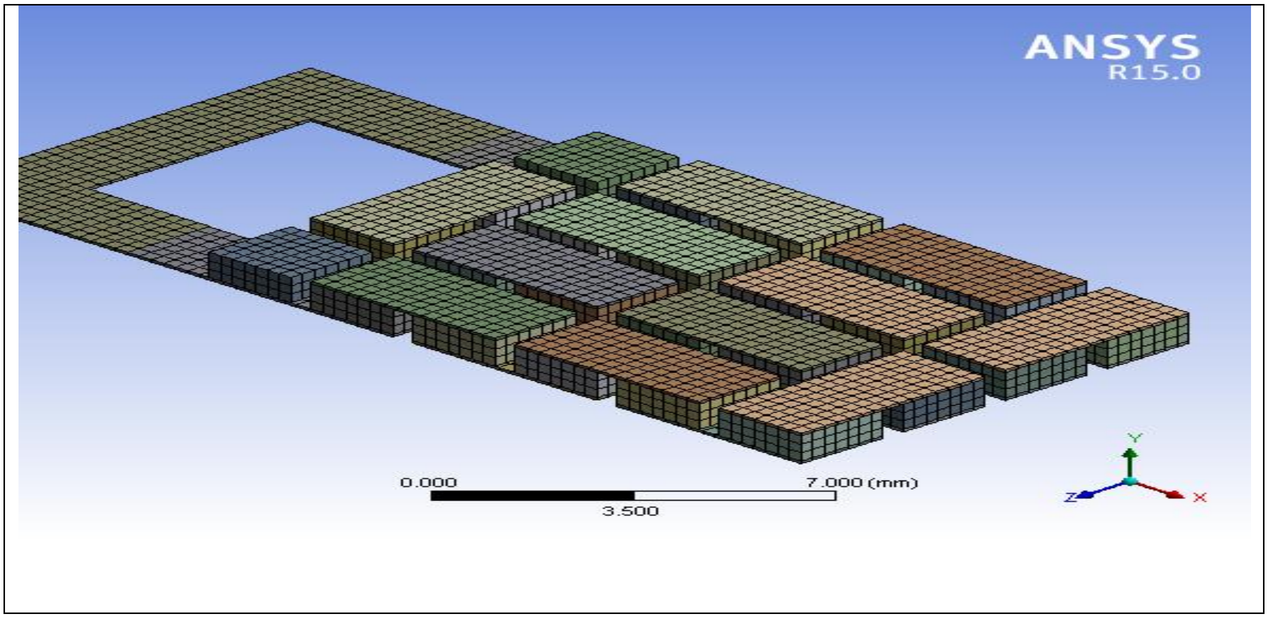

FIGURE 4. Meshed component

Input boundary conditions for analysis:

The following are the boundary conditions given

- Source temperature is set to 700^0C
- Sink temperature is set to 30^0C
- Zero voltage boundary condition is to be given in ANSYS.

Simulation is done using ANSYS APDL in thermal electrical analysis.

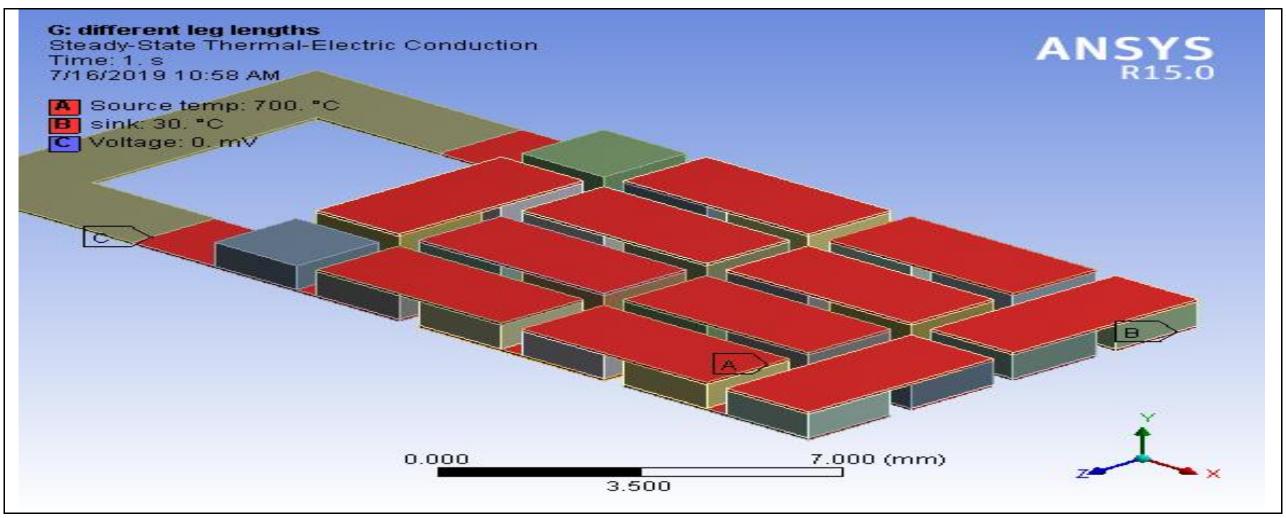

FIGURE 5. Boundary conditions for TEG Module

Analytical modeling:

Analytical modeling is done by solving governing equations in Microsoft excel. The equations have been verified and presented in [7]. The governing equations are as shown below.
Thermal conductivity of P and N type semiconductor is assumed to be constant.

Governing equations:

Following governing equations are used.
If T_h is source temperature
If T_L is sink temperature
Current is calculated by $I = \frac{(\alpha P - \alpha N)(Th - TL)}{Rp + Rn + RL}$ ……………………………………………………………..…..1
Power = $I^2 R_L$
If Q_h is heat supplied to source
$Qh = \alpha_p I T_h - \frac{I2Rp}{2} + k(T_h - T_L)$……………………………………………………………………………………2
If Q_c is the heat rejected at the sink
$Qc = \alpha_n I T_L - \frac{I2Rp}{2} + k(T_h - T_L)$……………………………………………………………………………………3
Power is calculated as
$P = Q_h - Q_c$……………………………………………………………………………………………..…4

RESULTS AND DISCUSSION

Analysis is done using ANSYS and also mathematically using formulae. Power produced is analyzed for with variation of load resistance and leg length is analyzed. The results obtained by ANSYS are validated using analytical formulas.

Power Output for Constant Leg Length

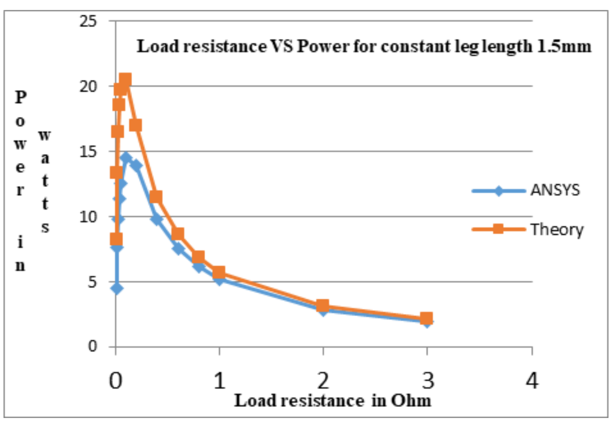

FIGURE 6. Load resistance VS Power for constant leg length 1.5mm

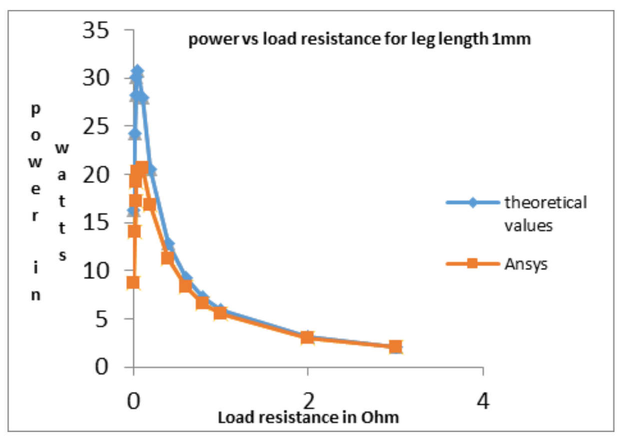

FIGURE 7. Load resistance VS Power for constant leg length 1mm

From the Fig 6, it can be observed that by varying the load resistance power can be varied. Power is maximum for load resistance of 0.1 Ohm for a leg length of 1.5mm with source temperature is $T_h = 700^oC$ and $T_c = 30^oC$. It is observed that the results obtained by ANSYS and analytical methods are almost same and the minor variation is due to meshing. From the Fig 7, it is observed that power is maximum for load resistance of 0.1 Ohm for a leg length of

1mm with source temperature $T_h = 700^oC$ and $T_c = 30^oC$. The results obtained by ANSYS and analytical methods are almost same at load resistance more than 0.5 Ohm, but there is variation at low resistance. It is because as the resistance reduces, errors became dominant. The peak obtained for both ANSYS and analytical is at 0.06 ohm load resistance.

Similarly graphs are plotted for different leg length of 1mm, 1.25mm and 1.5mm. The values are calculated using ANSYS and by mathematical formulae. In all calculations source and sink temperatures, and material properties are kept constant.

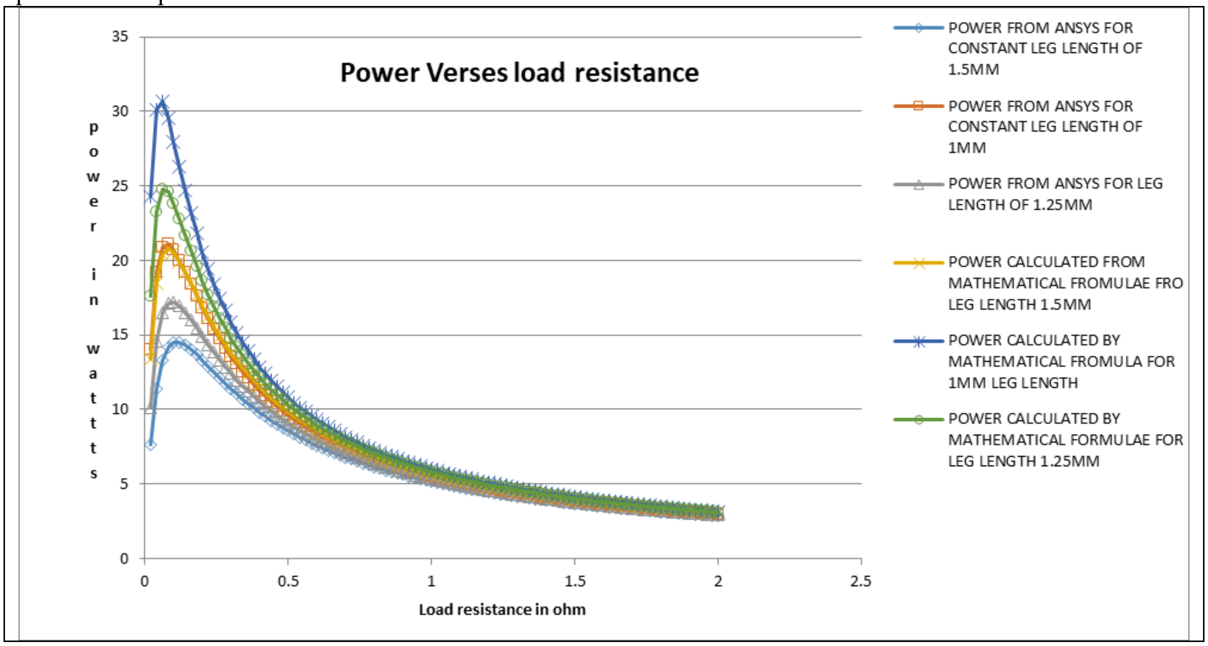

FIGURE 8. Power Vs Load resistance for different leg lengths

Power Output for Constant Load Resistance

From Fig 9, it can be observed that by variation of leg length there is variation in the power output. Power output increases with decrease in the leg length. Source temperature $T_h=700^oC$ and $T_c=30^oC$. The results are for a load resistance of 0.4 Ohm**.**

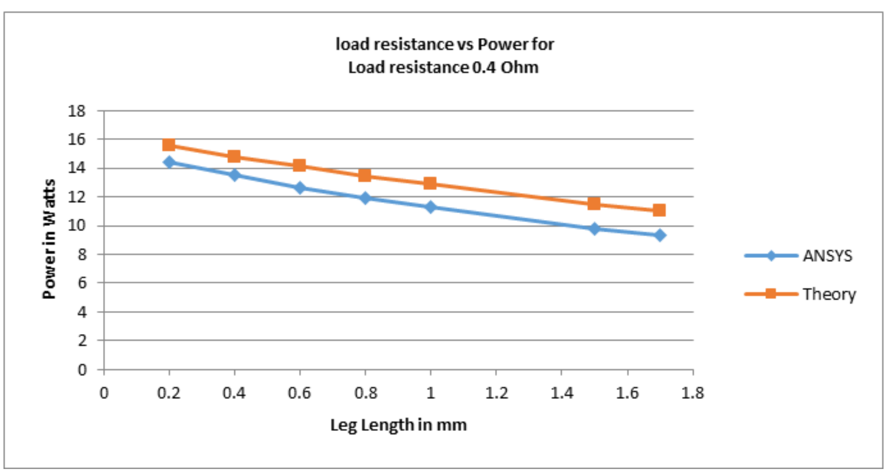

FIGURE 9. Load resistance vs Power for Load resistance 0.4 Ohm

CONCLUSIONS

By the analysis of thermoelectric generator using ANSYS and zero dimensional mathematical model, it concluded that for a thermoelectric generator there is an optimum load resistance at which power produced is maximum. For every leg length there is a load resistance at which power produced is maximum. For a leg length of 1.5mm the peak power is obtained for both ANSYS and analytical is at 0.1ohm load resistance. For a leg length of 1mm the peak power is obtained at 0.06 ohm load resistance. We can see that the results obtained by ANSYS and analytical methods are almost same at load resistance more than 0.5ohm but there is variation at low resistance. It is because as the resistance reduces errors of numerical simulation became dominant. Also for a given load resistance there is increase in power as the leg length decreases but practically to maintain temperature gradient for small leg length will be difficult.

REFERENCES

1. Advanced Technologies and Energy Efficiency, Fuel Economy Guide. US Dept. of Energy. (2009). Retrieved 2009-12-02.
2. Global Termoelectruic Materials Market, Research and Markets Report [2018]
3. DiSalvo, F.J., Science, 285, 703- 706 (1999).
4. D.M. Rowe, CRC Handbook of Thermoelectrics, CRC Press, USA (1995).
5. A. J. Minnich, M. S. Dresselhaus, Z. F. Ren and G. Chen, Energy and Environment, 2, 466 – 479 (2009).
6. Fankai Meng, Lingen Chen, Fengrui Sun, Energy, 36(5), 3513-3522 (2011)
7. *Thermoelectric,* Ansys (NASDAQ: ANSS), Release 16.
8. T. O. discretization, *Ansys Help Viewer,* Release *Canonsburg, PA,* 2016.
9. H. Lee, Thermoelectrics: Design and Materials, John Wiley and Sons (2016).
10. AF Loffe, Measurement techniques of Thermoelectric Materials,1950
11. Seconded European standardization expert in India, http://sesei.eu/ [Accessed on 30-10-2019] (2018)
12. Samson Shittu et al. Journal of Power Sources, 428, 53–66 (2019).
13. Xingfei Yua, et al., Applied Thermal Engineering, 144, 647–657 (2018).
14. Gequn Shu, et al. Energy, 160, 612-624 (2018).
15. Y.J. Cui, et al., International Journal of Heat and Mass Transfer 137, 979–989 (2019).
16. Guangxi Wu, Xiong Yu, International Journal of Heat and Mass Transfer 137, 979–989 (2019).