Simulation of Heat Dissipation for a Satellite using Carbon Nanotube Nanofluids

To Anh Duc[***], Bui Hung Thang[*], Cao Thi Thanh[*] and Phan Ngoc Minh[**]

[*] Institute of Materials Science (IMS), Vietnam Academy of Science and Technology (VAST),
A2 Building, 18 Hoang Quoc Viet Road, Cau Giay District, Hanoi, Vietnam
[**] Graduate University of Science and Technology (GUST), Vietnam Academy of Science and Technology (VAST),
2B Building, 18 Hoang Quoc Viet Road, Cau Giay District, Hanoi, Vietnam
[***] Vietnam National Space Center (VNSC), Vietnam Academy of Science and Technology (VAST),
2B Building, 18 Hoang Quoc Viet Road, Cau Giay District, Hanoi, Vietnam

DOI: 10.29322/IJSRP.10.03.2020.p9997
http://dx.doi.org/10.29322/IJSRP.10.03.2020.p9997

Abstract **-** Satellites cope with harsh environment when working in the orbit so they require heat management by varios methods such as heat pipes, louvers, pumped fluid loop, etc… to improve stability, durability and longevity. The pumped fluid loop (PFL) is one of the most significant components as it is more efficient than other passive thermal control as it can deal with environmental extremes or to accommodate equipment dissipating high power. Carbon nanotube (CNT) is known as the material that has high thermal conductivity (k_{CNT} = 2000W/mK), so it is possible to use as nano-additive for enhancing thermal conductivity of fluids. In this report, we present some results on simulation of heat dissipation for a satellite using carbon nanotube nanofluids. These results open the potential application of CNTs in nanofluids for heat management in PFL of satellites.

I. Introduction

Thermal management is control is generally considered to be a crucial part of designing electronic systems, where each device's perfomance varies considerably depending on temperature. Furthermore, the lifetime of the electronic devices can be reduced due to the high operating temperature. Finding new materials with high thermal conductivity has become an important to improve heat management efficiency for electronic devices. [1]

Satellites are one of the electronic devices that have to survive in the extreme environment when working in orbit. They requires heat management by varios methods such as heat pipes, louvers, pumped fluid loop, etc… to improve stability, durability and longevity. The pumped fluid loop (PFL) is one of the most significant components as it is more efficient than other passive thermal control as it can deal with environmental extremes or to accommodate equipment dissipating high power. Improving the thermal conductivity of fluids will help improve the heat management efficiency of the PFL system. [2]

Nanofluid is a colloidal mixture of nanometre-sized (<100 nm) metallic and non-metallic particles in conventional fluid. Nanofluids are considered to be potential heat transfer fluids because of their superior thermal and tribological properties. Nanoparticles are made from different materials, for example, carbonnanotubes, metals, semiconductors, nitride ceramics, oxide ceramics, carbide ceramics, and composite materials. Nanofluids improved thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients, in comparison to those of base fluids like oil or water [2-7].

Carbon nanotube (CNT) is known as the material that has high thermal conductivity (k_{CNT} = 2000W/mK) in comparison with thermal conductivity of silver is 419 W/m.K [8-11], so it is possible to use as nano-additive for enhancing thermal conductivity of fluids [12-15].

Initial results on simulating the dissipation of heat using carbon nanotube nanofluids for a small satellite is showed in this article.

II. METHOD OF SIMULATION

Figure 1 shows the diagram of a PFL system for a satellite using carbon nanotube nanofluids. In this configuration, we arrange for the heat-sink to touch a heat source (satellite's power electronic component). The nanofluid was pumped from heat-sink to radiator-cover of satellite by using a fluid-pump. Inside the heat-sink, the track was made so that nanofluids could run through and take in the heat from electronic component that generate high power, then the nanofluids will flow from the heat-sink to satellite's cover for heat emission and returns back to the nanofluid-container.

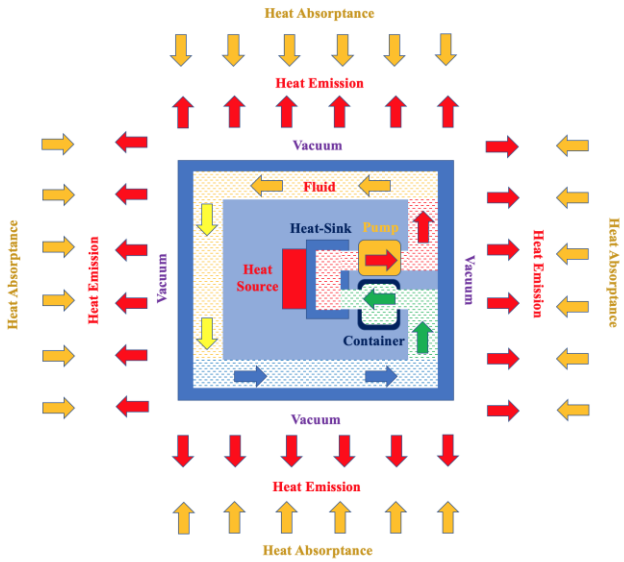

***Figure 1.** Diagram of the PFL system for a satellite using carbon nanotube nanofluids*

For the simplification of the simulation process, we worked on the assumption that the heat exchange process occurs only in heat-sink and satellite's cover. To run the simulation, the operating time of electronic component is broken into small differential times (Δt). The heat transfer equations were calculated by dedicated software in each very short differential time. Results of the simulation are reached by repeating the above processes multiple times.

We worked on the assumption that:

+ v is the flow-rate of nanofluids (m^3/s)
+ Δt is the diffential time in our simulation (s)
+ ΔV is the amount of fluid that flows in Δt (m^3)

We have:

$$\Delta V = v.\Delta t \tag{1}$$

The heat transfer equation showing the relationship between the volume of nanofluid ΔV that flows from the nanofluid-container to the heat sink and nanofluids in the heat-sink is as follows:

$$T_h^{'} = \frac{C_0 D_n \left[(V_h - \Delta V) T_h + \Delta V . T_c \right] + C_h . T_h}{C_0 D_n . V_h + C_h} \tag{2}$$

Where:

+ V_h is the volume of nanofluids in the satellite heat-sink (m^3)
+ T_h is the nanofluid's temperature in the satellite heat-sink (°C)
+ T'_h is the nanofluid's temperature in the satellite heat-sink after ΔV (the volume of nanofluids) flowing from the nanofluid-container to the satellite heat-sink (°C)
+ T_c is the nanofluid's temperature in the nanofluid-container (°C)
+ C_h is the heat capacity of the satellite heat-sink (J/K)
+ C_0 is the specific heat capacity of nanofluids (J/kg.K)
+ D_n is the density of nanofluids (kg/m^3)

We calculate the amount of heat that flows from electronic component to nanofluids as follows:

$$I_{p-h} = \frac{(T_p - T_h^{'})}{R_{p-h} + R_h + R_n} \tag{3}$$

Where:

+ I_{p-h} is the amount of heat that flows from satellite heat source to nanofluids in the satellite heat-sink (W)
+ T_p is the temperature of the satellite heat source (°C)
+ R_{p-h} is the heat resistance of the contact layer between satellite heat source and the satellite heat-sink (K/W)
+ R_h is the heat resistance of the satellite heat-sink (K/W)
+ R_n is the effective heat resistance of nanofluid (K/W)

We calculate the effective heat resistance of nanofluids as follows:

$$R_n = \frac{1}{2}.\frac{1}{k}.\frac{d}{S} = \frac{1}{2}.\frac{1}{k}.\frac{d}{a.b} \tag{4}$$

Where:

+ k is the thermal conductivity of the nanofluid (W/mK)
+ d is the thickness of the nanofluid in the satellite heat-sink (m)
+ S is the cross-sectional area of the nanofluid in the satellite heat-sink (m^2)
+ a, b are the width and length of the nanofluid in the satellite heat-sink, respectively (m)

We have:

$$T_p^{'} = T_p + \frac{\Delta Q}{C_p} = T_p + \frac{(P - I_{p-h})\Delta t}{C_p} \tag{5}$$

Where:

+ T'_p is the temperature of the satellite heat source after very short differential times Δt (°C)
+ ΔQ is the retain heat in the satellite heat source (°C)
+ C_p is the heat capacity of the satellite heat source (J/K)
+ P is the heat generation power of the satellite heat source (W)

We calculate the nanofluid's temperature in the satellite heat-sink after a brief period of differential time Δt as follows:

$$T_h^{''} = T_h^{'} + \frac{\Delta Q_h}{C_h + C_n} = T_h^{'} + \frac{I_{p-h}.\Delta t}{C_h + C_n} \tag{6}$$

$$T_h^{''} = T_h^{'} + \frac{I_{p-h}.\Delta t}{C_h + C_0 D_n . V_h} \tag{7}$$

Where:

+ T''_h is temperature of the nanofluid in the satellite heat-sink after very short differential times Δt (°C)
+ ΔQ_h is the heat from satellite heat source to nanofluid and the satellite heat-sink (J)
+ C_n is the heat capacity of the nanofluid in the satellite heat-sink (J/K)

The heat transfer equation showing the relationship between nanofluids in satellite's radiator -cover and nanofluid volume ΔV that flows from heat-sink to satellite's radiator -cover is:

$$T_r^{'} = \frac{C_0 D_n \left[(V_r - \Delta V) T_r + \Delta V . T_h \right] + C_r . T_r}{C_0 D_n . V_r + C_r} \tag{8}$$

Where:

+ V_r is the volume of the nanofluid in satellite's radiator-cover (m^3)
+ T_r is the temperature of the nanofluid in satellite's radiator-cover (°C)
+ T_h is the temperature of the nanofluid flow from heat-sink to satellite's radiator-cover (°C)

+ T'_r is the temperature of the nanofluid in radiator-satellite's cover after the amount of ΔV nanofluid flowing from the satellite heat-sink to satellite's radiator-cover (°C)
+ C_r is the heat capacity of the satellite's radiator-cover (J/K)

The heat emission from satellite's radiator-cover to space is calculated by Stefan -Boltzmnann's Law:

$$I_{r-s} = \varepsilon\sigma A_r T_r^4 \quad (9)$$

Where:
+ I_{r-s} denote the heat emission from satellite's radiator-cover to space (W)
+ A_r denote the emissive area of satellite's radiator-cover (m^2)
+ σ denote the Stefan-Boltzmann constant
+ ε denote the emissivity of non-black body

The heat absorptance from space to satellite's radiator-cover is calculated by following formula:

$$I_{s-r} = \eta\phi A_r \quad (10)$$

Where:
+ I_{s-r} denote the heat absorptance from space to satellite's radiator-cover (W)
+ A_r denote the emissive area of satellite's radiator-cover (m^2)
+ ϕ denote the flux from space to satellite's radiator-cover (W)
+ η denote the absorptance of non-black body

We make the assumption that the shape of the liquid-track inside the radiator is rectangular. We calculate the effective heat resistance of nanofluids in the radiator as follows:

$$R_n' = \frac{1}{2}.\frac{1}{k}.\frac{d'}{S'} = \frac{1}{2}.\frac{1}{k}.\frac{d'}{a'.b'} \quad (11)$$

Where:
+ d' is the thickness of the nanofluid in the radiator(m)
+ S' is the cross-sectional area of the nanofluid in the radiator(m^2)
+ a', b' are the width and length of the nanofluid in the radiator, respectively (m)

We calculate the nanofluid's temperature in the radiator after a sport period of differential time Δt as follows:

$$T_r'' = T_r' - \frac{\Delta Q_{r-e}}{C_r + C_n'} = T_r' - \frac{(I_{r-s} - I_{s-r}).\Delta t}{C_r + C_n'} \quad (12)$$

$$T_r'' = T_r' - \frac{(I_{r-s} - I_{s-r}).\Delta t}{C_r + C_0 D_n.V_r} \quad (13)$$

Where:
+ T''_r is temperature of the nanofluid in the radiator after very short differential times Δt (°C)
+ ΔQ_{r-m} is the heat from radiator to environment (J)
+ C'_n is the heat capacity of the nanofluid in radiator (J/K)

The heat transfer equation showing the relationship between nanofluids in the container and nanofluid volume ΔV that flows from the radiator to the container is:

$$T_c' = \frac{C_0 D_n\left[(V_c - \Delta V)T_c + \Delta V.T_r\right] + C_c.T_c}{C_0 D_n.V_c + C_c} \quad (14)$$

Where:
+ V_c is the volume of the nanofluid in nanofluid-container (m^3)
+ T_c is the temperature of the nanofluid in nanofluid-container (°C)
+ T_r is the temperature of the nanofluid flow from radiator to nanofluid-container (°C)
+ T'_c is the temperature of the nanofluid in nanofluid-container after after very short differential times Δt (°C)
+ C_c is the heat capacity of the nanofluid-container (J/K)

III. RESULTS AND DISCUSSION

We chose CNTs-based propanol, the concentration of CNTs was from 0 .0 vol. % to 1. 0 vol % for the entire simulation. In the simulation process, the parameters are as follows:
+ The differential time of the simulation: $\Delta t = 10^{-8}$ (s)
+ The density of the nanofluid: D_n = 803 kg/m^3
+ The specific heat capacity of the nanofluid: C_0 = 2400 J/kg.K
+ The dimensions of the satellite heat-sink: a x b x c = 40 mm x 40 mm x 6 mm
+ The dimensions of liquid-track in the radiator: a x b x c = 30 mm x 5 mm x 0.5 mm
+ The volume of nanofluid-container: V_c = 0.1 litter
+ The heat power of satellite heat source: P = 20 W
+ The the flow-rate of the nanofluid: v = 5 (cm^3/s)
+ The heat emission and heat absorptance between satellite's radiator-cover and space was balanced at T_r = 30°C.
+ The initial tempertature of satellite's satellite heat source was equal to the tempertature of satellite's radiator-cover is 30°C

We calculated the thermal conductivity of nanofluids as follows [16]:

$$\frac{k}{k_w} = 1 + \frac{1}{3}\frac{k_{CNT}\varepsilon r_w}{k_w(1-\varepsilon)r_{CNT}} \quad (15)$$

Where:
+ k_w= 0.14 W/mK, is the thermal conductivity of propanol.
+ k_{CNT}= 1750 W/mK, is the thermal conductivity of CNT.
+ r_w= 0.15 nm, is the radius of water molecule.
+ r_{CNT}= 5 nm, is the average radius of CNT.
+ ε= 0.0 vol. % ÷ 1.0 vol. %, is the volume concentration of CNTs in nanofluid.

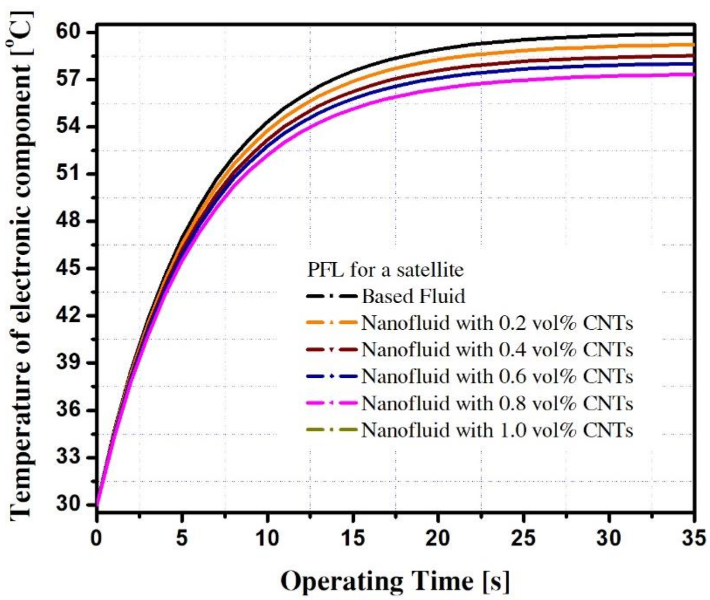

Figure 2. *Simulation result on heat dissipation for a satellite using carbon nanotube nanofluid*

Figure 2 shows the results of heat dissipation being simulated for electronic component using carbon nanotube nanofluid in a satellite. As can be seen in the figure, the temperature of electronic component increased exponentially. When the satellite is in orbit, the saturation temperature of electronic component is usually reached after a period of 35 minutes. As shown in Figure 2, we recorded a decrease in the saturation level of electronic component when we increased the concentration of CNTs. One possible explanation is that when we added CNTs into nanofluids, its thermal conductivity increased. This increase then improved the heat transfer at the substrate and radiator-cover of the satellite. Simulation results also showed as shown in figure 2, the saturated temperature of electronic component dropped by about 1°C to 3.5°C. When replacing based-fluid by nanofluids with 1.0 vol. % of CNTs, we have recorded that the saturated temperature of electronic component dropped by 3.5ºC.

IV. CONCLUSION

The thermal dissipation for for a satellite using carbon nanotube nanofluids was simulated. Simulation results showed that the saturated temperature of electronic component dropped by about 1°C to 3.5°C, concentrations of CNTs were (0.0 vol. %) to (1.0 vol. %) in nanofluids. The saturated temperature of electronic component dropped by 3.5ºC when we use nanofluids with vol. % of CNTs compare to only using based fluid. The above results of our simulation have shown the considerable benefit that CNTs can bring about as an additive component in nanofluids for dissipating heat in PFL.

ACKNOWLEDGMENT

The research was financially supported by the VAST under grant No VAST01.08/18-19.

REFERENCES

[1] Y Shabany, *Heat transfer: thermal management of electronics*, CRC Press, Taylor & Francis Group (2009).

[2] Kawthar Kasim, Arun Muley, Michael Stoia, Foluso Ladeinde, *Advanced Heat Transfer Devices for Aerospace Applications*, IMECE2017-72382, V008T10A027, 7 (2017)

[3] Muhammad Usman Sajid, Hafiz Muhammad Ali, *Recent advances in application of nanofluids in heat transfer devices: A critical review*, Renewable and Sustainable Energy Reviews 103, 556-592 (2019)

[4] Z. Iqbal, E. N. Maraj, Ehtsham Azhar, Zaffar Mehmood, A novel development of hybrid MoS_2 – SiO_2/H_2O nanofluidic curvilinear transport and consequences for effectiveness of shape factors, Journal of the Taiwan Institute of Chemical Engineers 81, 150-158 (2017)

[5] P. Naphon, S. Wiriyasart, T. Arisariyawong, L. Nakharintr, *ANN, numerical and experimental analysis on the jet impingement nanofluids flow and heat transfer characteristics in the micro-channel heat sink*, International Journal of Heat and Mass Transfer 131, 329-340 (2019)

[6] M. M. Sarafraz, M. Silakhori, S. A. Madani, M. V. Kiamahalleh & O. Pourmehran, *Thermal and hydraulic performance of a heat exchanger working with carbon-water nanofluid*, Heat and Mass Transfer volume 55, pages3443–3453(2019)

[7] Seshu Kumar, Suhaimi Bin Hassan, KV Sharma, Aklilu Baheta, *Heat Transfer Coefficients Investigation for TiO2 Based Nanofluids*, International Journal of Engineering, doi: 10.5829/IJE.2019.32.10A.19 (2019)

[8] A. N. Omrani, E. Esmaeilzadeh, M. Jafari, A.Behzadmehr, *Effects of multi walled carbon nanotubes shape and size on thermal conductivity and viscosity of nanofluids*, Diamond and Related Materials 93, 96-104 (2019)

[9] Yinhang Zhang, Young-Jung Heo, Yeong-Rae Son, Insik In, Kay-Hyeok An, Byung-Joo Kim, Soo-JinPark, *Recent advanced thermal interfacial materials: A review of conducting mechanisms and parameters of carbon materials*, Carbon 142, 445-460 (2019).

[10] A. N. Omrani, E. Esmaeilzadeh, M. Jafari, A. Behzadmehr, *Effects of multi walled carbon nanotubes shape and size on thermal conductivity and viscosity of nanofluids*, Diamond and Related Materials 93, 96-104 (2019)

[11] Normah Mohd-Ghazali, Patrice Estellé, Salma Halelfadl, Thierry Maré, Tng Choon Siong, Ummikalsom Abidin, *Thermal and hydrodynamic performance of a microchannel heat sink with carbon nanotube nanofluids*, 2002, Journal of Thermal Analysis and Calorimetry 138, 2, 937–945 (2019)

[12] To Anh Duc, Nguyen Viet Phuong, Cao Thi Thanh, Bui Hung Thang, Phan Ngoc Minh, *A model for the thermal conductivity of mixed fluids containing carbon nanotubes*, Computational Materials Science 165, 59–62 (2019).

[13] Pham Van Trinh, Nguyen Ngoc Anh, Nguyen Tuan Hong, Phan Ngoc Hong, Phan Ngoc Minh, Bui Hung Thang, *Experimental study on the thermal conductivity of ethylene glycol-based nanofluid containing Gr-CNT hybrid material*, Journal of Molecular Liquids 269, 344–353, (2018)

[14] Pham VanTrinh, Phan Ngoc Hong, Nguyen NgocAnh, Nguyen Trong Tam, Nguyen Tuan Hong, Phan Ngoc Minh, *Influence of defects induced by chemical treatment on the electrical and thermal conductivity of nanofluids containing carboxyl-functionalized multi-walled carbon nanotubes*, RSC Adv. 7, 49937 (2017)

[15] Pham Van Trinh, Nguyen Ngoc Anh, Bui Hung Thang, Le Dinh Quang, Nguyen Tuan Hong, Nguyen Manh Hong, Phan Hong Khoi, Phan Ngoc Minh and Phan Ngoc Hong, *Enhanced thermal conductivity of nanofluid-based ethylene glycol containing Cu nanoparticles decorated on a Gr–MWCNT hybrid material*, RSC Adv. 7, 318 (2017)

[16] Bui Hung Thang, Phan Hong Khoi, and Phan Ngoc Minh, *A modified model for thermal conductivity of carbon nanotube-nanofluids*, Physics of Fluids 27, 032002 (2015)

AUTHORS

First Author – M.Si. To Anh Duc, Research scholar, Vietnam National Space Center (VNSC), Vietnam Academy of Science and Technology (VAST).
Second Author – Dr. Bui Hung Thang, Center of Application and Development of Technology, Institute of Materials Science (IMS), Vietnam Academy of Science and Technology (VAST).
Third Author – Dr. Cao Thi Thanh, Laboratory for Developing Advanced Materials Technology, Center for High Technology Development (HTD), Vietnam Academy of Science and Technology (VAST).
Fourth Author – Dr. Phan Ngoc Minh, Professor, Graduate University of Science and Technology (GUST), Vietnam Academy of Science and Technology (VAST).

Correspondence Author – Dr. Bui Hung Thang
Email: thangbh@ims.vast.vn, thangbh@ims.vast.ac.vn
Mobile phone: +84 985175655