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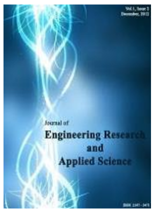

Investigation into the Use of R-1234ze Refrigerant in Laptop Heat Pipes

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Abstract

Laptops, especially their processors and other electronic circuit elements, constantly generate heat in a limited space and can reach very high temperatures. These extreme temperatures and the heat generated by these temperatures can cause serious damage to the computer's electronic system. Therefore, it is very important to effectively transfer thermal energy to the environment and reduce system temperatures to safe operating levels to ensure the continued functionality of electronic systems and components. To achieve this, heat pipes are often preferred for cooling in computer systems. This study experimentally compared the usability and thermal performance of the new generation R-1234ze coolant instead of the existing water-methanol mixed liquid in the heat pipe of a Levona brand laptop. The experiments were conducted under idle, normal load (video viewing), and maximum load operating conditions. In each of these environments, temperature measurements were made from thermocouples placed at four different points on the heat pipe every 5 seconds for 20 minutes. The internal CPU temperature of the laptop and temperatures at four different points on the heat pipe were evaluated for both the water-methanol fluid and R-1234ze refrigerant. Experimental studies were carried out for water-methanol mixture fluid and R-1234ze, and the results were compared. Furthermore, a natural convection heat transfer analysis was performed, comparing the Nusselt number and heat transfer coefficient for both cases. In addition, natural convection heat transfer analysis was performed to compare the Nusselt number and heat transfer coefficient for both cases. The experimental results show that the R-1234ze coolant can be used effectively in notebook computer heat pipes and has very good thermal performance.

Keywords: *Heat pipe, Laptop, Water-methanol, R-1234ze, Thermal analysis*

1. Introduction

Today, heat pipes are used in many sectors such as industry, electronics, and the computer field. In particular, the size and weight of laptops are gradually decreasing. Therefore, this geometrical reduction requires heat pipes to be more efficient and smaller in size, but more functional. Heat pipes are a single-piece part used in laptops to efficiently cool very hot laptop parts such as the CPU processor, and graphics card. These pipes facilitate effective heat transfer due to their small size and lightweight structure and play an important role in cooling the computer unit. Due to the increasing capacity and speed in laptops, the processor and other electronic circuit components can reach high temperatures by constantly generating heat in a limited area. These extreme temperatures and heat can seriously damage the electronic components of the computer. Therefore, it is important to effectively transfer heat energy to the environment and reduce system temperatures to safe operating levels to ensure the continuous operation of electronic systems and components. For this purpose, heat pipes are preferred for cooling in computer systems. Due to the thinness, lightness, and small dimensions of laptop computers, the reduction in size and increase in component density have led to enormous heat flux values for modern electronic and photonic devices [1]. Electronic circuit elements can reach very high temperatures by continuously generating heat in a limited area, which can cause serious damage to the electronic system in which these elements are located. In addition, cooling at the laptop processor chip level is the biggest bottleneck for the proper functioning of devices due to the formation of local hot spots with large temperature gradients on the chip [2, 3].

To ensure the continuous operability of electronic components and systems, the generated heat energy

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must be effectively transferred to the environment, and the systems must be brought down to safe temperature levels. Performance measurements of computer processors have shown that a 10 °C temperature drop increases the operating speed of the circuit by an average of 2% [4]. The working fluid for a heat pipe is selected according to its operating temperature range. The selection of the working fluid is also critical for the proper functioning of the heat pipe and for establishing the capillary mechanism; the liquid phase of the working fluid must wet the body material [5].

The heat transfer performance of heat pipes is related to various physical parameters such as heat pipe configuration, geometric characteristics, operating parameters, physical dimensions, fin additions, tube material, and number of turns. Performance measurements of computer processors have shown that a 10 °C temperature drop increases the operating speed of the circuit by an average of 2% [6]. Experimental studies have been conducted on the heat transfer capacity for a flat disk evaporator loop heat pipe [7].

Recently, the results of loop heat pipe studies with different working fluids found in the literature are presented below in Table 1.

Table 1. Recent loop heat pipe studies with different working fluids in literature

Evaporator Shape/Material	Working Fluid	Max. Heat Load	Max. Temperature	Source
Disk / Brass	Water	120 W	85 °C	[8]
Disk / Brass	Methanol	160 W	85 °C	[9]
Disk / Copper	Methanol	160 W	90 °C	[10]
Disk / Copper	Water	140 W	90 °C	[11]
Rectangular / Stainless Steel	Acetone	280 W	100 °C	[12]
Rectangular / Copper	Water / Methanol / Ethanol	900-380-320 W	95 °C	[13]
Rectangular / Copper	Water–Copper nanofluid	100 W	66.1 °C	[14]
Rectangular / Copper	Water	75 W	110 °C	[15]
Rectangular / Copper	Water	150 W	85 °C	[14]

2. Experimental Study

The experimental work utilized an Intel Core laptop. specifications detailed in Table 2, a data-logging thermocouple-thermometer, and the FurMark2 stress test program to generate maximum CPU workload.

Core Temp software was employed for monitoring CPU temperature, and a Techsun analog pressure-temperature gauge was used for relevant measurements.

Table 2. Specifications of the Intel Core laptop

Feature	Specification
Processor Brand	Intel
Processor Model	2410M
Processor Speed	2.30 GHz
Graphics Card Chipset	AMD®, HD6370
Graphics Card Memory	1024 MB
RAM Type	DDR3
Disk Capacity	500 GB
Screen Size	15.6 inches
System Memory (RAM)	4 GB

2.1. Thermocouple-Thermometer Measurement Device

Temperature measurements in the experimental setup were conducted using a digital measuring device, whose brand is a Cem DT3891G, as shown in Figure 1. The specifications of the thermocouple-thermometer used in the experiments are provided in Table 3. This device functions as a data-logging thermocouple-thermometer and features four integrated thermocouple probes.

Figure 1. A photograph of the thermocouple-thermometer device used in the experiments.

The thermocouple-thermometer alternately displays temperature readings from these four probes in a dual-view format.

2.2. Experimental Setup

A photograph of the heat pipe used in the experiment, along with its assembled state within the experimental setup, is presented in Figure 2. The FurMark stress test program (v2.4.3) was utilized to generate maximum workload on the laptop's CPU.

Table 3. Technical specifications of the CEM thermocouple and datalogger.

Feature	Specification
Temperature Accuracy	±1 °C
Temperature Resolution	0.1 °C
K-Type Thermocouple Range	−200 °C to +1372 °C
J-Type Thermocouple Range	−210 °C to +1100 °C
Display	Backlit LCD
Sensor Cable Length	98 cm
Memory Capacity	18,000 readings per thermocouple input
Max/Min Functionality	Yes
°C/°F Unit Conversion	Yes
Storage Temperature	−10 °C to +50 °C
Operating Temperature	0 °C to +50 °C

Traditionally, a water-methanol mixture is employed in laptop heat pipes. In this experimental study, a homogeneous mixture of methanol and water with a methanol volume ratio of 73% was charged into the laptop heat pipe at a pressure of 50 kPa. As an alternative working fluid, the next-generation R-1234ze was loaded into the heat pipe under vacuum. Considering the balance of its properties, R-1234ze is considered the best medium-pressure, low Global Warming Potential (GWP) refrigerant available on the market. It serves as an energy-efficient alternative to conventional refrigerants for various medium-temperature applications and has been selected by numerous equipment manufacturers for applications ranging in capacity from a few kilowatts to 20 MW and with charges varying from 300 grams to 13 megatons.

Its application areas include air-cooled and water-cooled chillers, district heating and cooling, heat pumps, refrigerators, vending machines, beverage dispensers, and air dryers, among others. R-1234ze has received numerous industries awards and meets key user criteria such as performance, cost-effectiveness, environmental impact, and safety. According to ASHRAE Standard 34 (ISO 817), R-1234ze is classified as non-flammable. However, it can ignite when mixed with pressurized air and exposed to strong ignition sources.

Figure 2. Presents images of the laptop's heat pipe, both as a standalone component and following its integration into the experimental setup.

2.3. Temperature Measurement Method

For the thermal analysis of the laptop's heat pipe, a total of four thermocouples were utilized. This arrangement is crucial for effectively monitoring heat transfer and distribution. One of these thermocouples was placed on the electronic circuit cooling plate (T1), another on the laptop's CPU processor (T2), one in the middle of the heat pipe (T3), and the remaining one was mounted near the computer fan (T4). The connection of the thermocouples with digital temperature displays to the heat pipe in the laptop is illustrated in Figure 3.

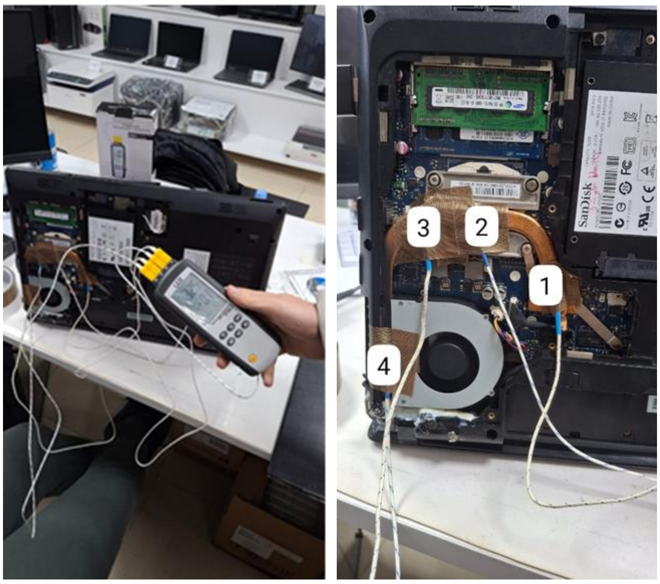

Figure 3. Four thermocouple connections with a digital temperature display are connected to the heat pipe on the laptop.

Temperatures were recorded at specific time intervals using a digital thermometer with a display connected to the thermocouples mounted on the heat pipe. Measurements were taken under three distinct operating conditions: a) When the laptop was operating at idle, b) normal load (video viewing), and c) under maximum load using the FurMark stress test program.

To analyze temperature variations over time, data from all four thermocouples were recorded every 5 seconds. These tests were conducted over 20 minutes, yielding 240 temperature data points for each test condition.

3. Natural Convection Heat Transfer in the Heat Pipe

Heat transfer by natural convection within a heat pipe occurs due to density differences in the fluid, which are induced by temperature variations, leading to fluid motion. In such systems, heat transfer from the outer surface to the ambient air is typically facilitated by natural convection. The fundamental equations describing this process, along with the definitions of their symbols, are provided below:

The film temperature (T_f) is the average of the surface temperature and the ambient temperature.

$$T_f = \frac{(T_S - T_\infty)}{2} \quad (1)$$

The Grashof number (Gr) represents the ratio of buoyant forces, arising from temperature-dependent density differences to the viscous resistive forces within the fluid. An increase in this number indicates a stronger natural convection effect. It is expressed by the following equation [16]:

$$Gr = \frac{g\beta(T_S - T_\infty)L^3}{\nu^2} \quad (2)$$

Here, g is the gravitational acceleration, β is the volumetric thermal expansion coefficient (1/T), T_s is the surface temperature (outer surface of the heat pipe), T_∞ is the ambient temperature (air), L is the characteristic length, and ν is the kinematic viscosity.

The Rayleigh number (Ra) determines whether natural convection will initiate and its effectiveness. Convection begins if this number exceeds a certain critical value (the transition region is approximately between ≈10^3 and 10^4).

$$Ra = Gr.Pr \quad (3)$$

Here, Pr is the dimensionless Prandtl number.

The Churchill–Chu correlation for the Nusselt number (Nu) provides the ratio between the heat transfer coefficient (h) and the thermal conductivity (k). An increase in this number indicates a greater amount of heat transferred by convection. The recommended expression for a horizontal cylinder is given below [16]:

$$Nu = \left[0{,}6 + \frac{0{,}387Ra^{1/6}}{\left(1+\left(\frac{0{,}559}{Pr}\right)^{9/16}\right)^{8/7}}\right]^2 \quad (4)$$

The heat transfer coefficient (h) indicates the amount of heat transferred per unit area per unit time from the surface to the surroundings. A larger h signifies a more effective cooling of the surface.

$$h = \frac{Nu.k)}{L} \quad (5)$$

Here, k is the thermal conductivity coefficient.

The total heat transfer (Q) is the total amount of heat transferred from a specific surface area to the ambient environment via natural convection.

$$Q = h.A.(T_S - T_\infty) \quad (6)$$

Here, A is the surface area (outer surface of the heat pipe).

4. Results

The results present experimental data from the thermal analysis of a heat pipe, with temperature values obtained from four different points in a laptop computer using two working fluids: the original water-methanol mixture and the refrigerant R-1234ze, within an unmodified heat pipe structure. All experimental studies were conducted in a climate-controlled room, with the ambient temperature maintained at 20 °C throughout all tests. The graphical results of a total of 240 temperature measurements taken every 5 seconds for 20 minutes from four different points (T1, T2, T3, and T4) on the outer surface of the heat pipe containing a water-methanol mixture and R1234ze refrigerant.

4.1. Temperature analysis on the heat pipe in an idle environment

When the laptop was operating in an idle environment, temperatures were measured in four-point regions for a water-methanol mixture and R1234ze refrigerant as shown in Figure 4.

The overall average temperature measured across the entire heat pipe was calculated to be 33.92 °C for water-methanol mixture and 30.11 °C for R-1234ze refrigerant. Upon evaluating these temperature values, it was observed that the highest temperatures were, as expected, located at the portion of the laptop's heat pipe situated directly above the CPU. Conversely, the lowest temperatures were recorded at the far end of the heat pipe, which is integrated with the fan fins.

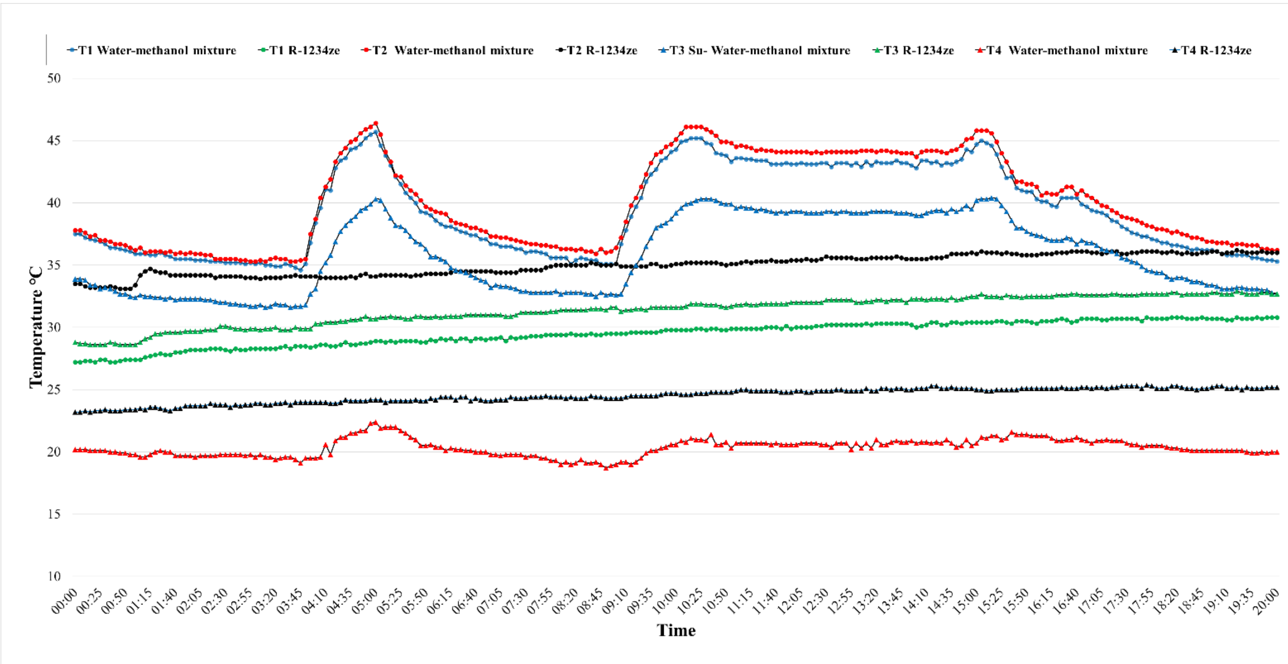

Figure 4. Time-temperature graph of the heat pipe in an idle operating environment with water-methanol fluid and R-1234ze refrigerant

4.2. Temperature analysis on the heat pipe in a normal (video viewing) environment

When the laptop was operating in a normal (video viewing) environment, temperatures were measured in four-point regions for a water-methanol mixture and R1234ze refrigerant as shown in Figure 5. The overall average temperature measured across the entire heat pipe was calculated to be 36.56 °C for water-methanol mixture and 47.93 °C for R-1234ze refrigerant. It was observed that the highest temperatures were located at the portion of the laptop's heat pipe situated directly above the CPU. The lowest temperatures were recorded at the end of the heat pipe, which is integrated with the fan.

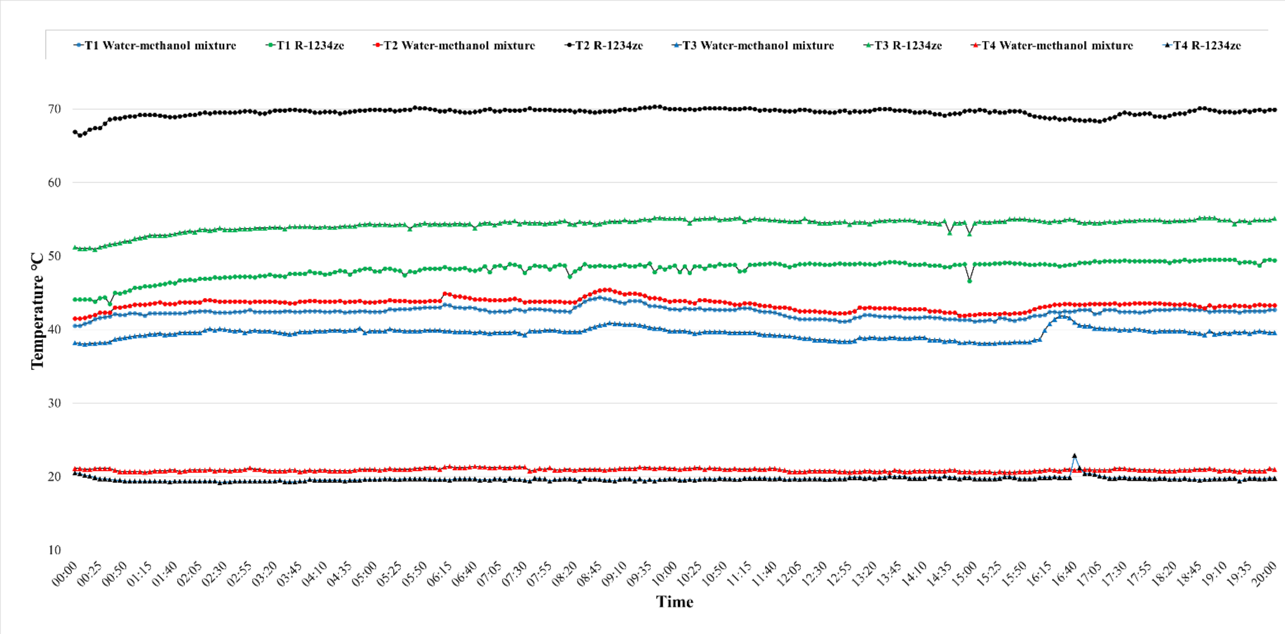

Figure 5. Time-temperature graph of the heat pipe in normal load (video viewing) operating environment with water-methanol fluid and R-1234ze refrigerant

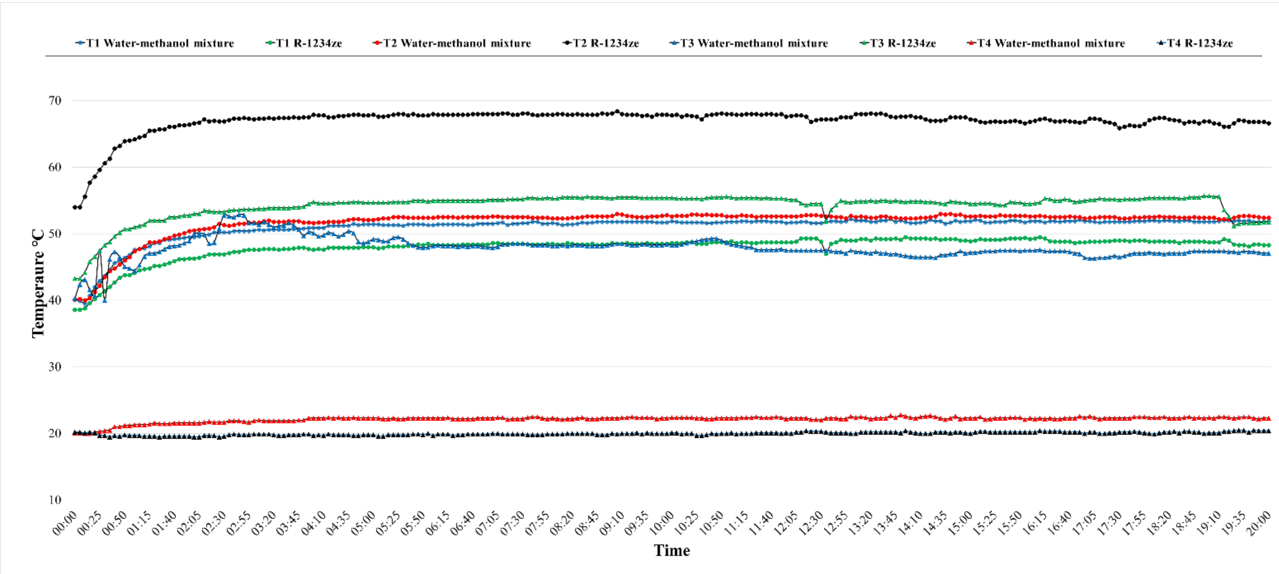

Figure 6. Time-temperature graph of the heat pipe in the maximum load operating environment with water-methanol fluid and R-1234ze refrigerant

4.3 Temperature analysis on the heat pipe in the maximum load environment.

When the laptop was operating in the maximum load environment, temperatures were measured in four-point regions for a water-methanol mixture and R1234ze refrigerant as shown in Figure 6. The overall average temperature measured across the entire heat pipe was calculated to be 43.21 °C for water-methanol mixture and 47.30 °C for R-1234ze refrigerant. It was observed that the highest temperatures were located at the portion of the laptop's heat pipe situated directly above the CPU. The lowest temperatures were recorded at the end of the heat pipe, which is integrated with the fan.

Table 4. Comparison of temperatures of two different fluids in the heat pipe of a laptop and different operating environments.

Operating environment	Measurement location	Parameter	Refrigerant temperatures (°C)	
			Water-methanol fluid	R-1234ze
Idle	T1	Maximum	45.7	30,8
		Minimum	34.6	27.2
		Average	39.38	29.51
	T2	Maximum	46.4	36.2
		Minimum	35.3	33.1
		Average	40.12	35.01
	T3	Maximum	40.4	32.9
		Minimum	31.6	28.6
		Average	35.83	31.38
	T4	Maximum	22.4	25.4
		Minimum	18.7	23.2
		Average	20.34	24.53
	Overall average temperature		33.92	30.11
Normal load (video viewing)	T1	Maximum	44.4	49.5
		Minimum	40.5	43.5
		Average	42.37	48.21
	T2	Maximum	45.4	70.3
		Minimum	41.5	66.4
		Average	43.43	69.52
	T3	Maximum	41.8	55.2
		Minimum	38.0	50.9
		Average	39.51	54.31
	T4	Maximum	21.4	22.9
		Minimum	20.5	19.2
		Average	20.93	19.69
	Overall average temperature		36.56	47.93
Maximum load	T1	Maximum	52.2	49.5
		Minimum	39.5	38.6
		Average	51.00	47.99
	T2	Maximum	53.0	68.4
		Minimum	40.0	54
		Average	51.75	66.97
	T3	Maximum	52.9	55.7
		Minimum	40.0	43.3
		Average	47.93	54.25
	T4	Maximum	22.8	20.5
		Minimum	20.0	19.5
		Average	22.15	19.99
	Overall average temperature		43.21	47.30

Table 4 presents the minimum. maximum. and an average of 240 temperatures recorded over 20 minutes for each fluid and working environment. as well as the overall average temperature measured throughout the entire heat pipe. taken from four different points along the heat pipe. Temperature measurements were made by taking data every 5 seconds for 20 minutes from the thermocouples on the heat pipe of the laptops in a climate-controlled room with a constant ambient temperature of 20 °C with two different fluids. When the data in Table 4 is compared. it is seen that when the average of the temperature measurements at four different locations of the heat pipe in the idle operating environment is evaluated. it is seen that Water-methanol > R-1234ze. It is seen that the fluid with the lowest average heat pipe surface temperatures in the idle environment is R-1234ze. It is seen that the heat transfer of the refrigerant R-1234ze in the idle environment is good and that it is effective in reducing the heat pipe temperature. As seen in Table 4. when the average of the temperature measurements at two different locations of the heat pipe in the normal (video viewing) environment and. are compared. it is seen that the low temperature average is in the water-methanol fluid heat pipe and the other fluids have temperature averages close to each other. It is seen that the average temperatures measured from the heat pipe surface in normal (video viewing) and maximum load operating environments is R-1234ze > Water-methanol. It is seen that the heat transfer values of the water-methanol fluid are good in normal (video viewing) and maximum load operating environments and that it is effective in reducing the heat pipe temperature.

4.4. Comparison of Heat Transfer Values with Natural Convection in Heat Pipe

By taking the arithmetic average of the temperatures at different locations (T1. T2. T3 and T4) on the outer surface of the heat pipe of the laptop. the calculated heat pipe average temperatures (seen in Table 4) and since the fixed ambient temperature is 20 °C. the heat transfer values in the heat pipe by natural convection were calculated with the help of the equations given in Equations 1-6 for four different refrigerants in idle. normal (while watching a video) and maximum load operating environments) as shown in Table 5.

Geometric properties of the heat pipe: Length (L): 239.165 mm, Hydraulic diameter: 3.348 mm, Wall thickness: 1 mm, hydraulic diameter: 5.348 mm, and surface area is 40.17 cm^2. The dimensionless Nusselt number and heat transfer coefficient results of all refrigerants are given as thermal analysis (heat transfer by natural convection). When the Nusselt number is examined in the idle operating environment. it is seen that the good fluid is R-1234ze refrigerant.

Table 5. Thermal analysis comparison of laptop heat pipe with two different fluids and different operating environments.

Operating Environment	**Parameter**	**Refrigerant temperatures (℃)**	
		Water-methanol fluid	**R-1234ze**
Idle	Film Temperature (T_f). K	309.025	298.205
	Density – Air (ρ). kg/m³	1.145	1.175
	Thermal Expansion Coefficient (β). K⁻¹	0.003259	0.003353
	Kinematic Viscosity (ν). m²/s	1.67×10^{-5}	1.58×10^{-5}
	Thermal Conductivity (k). W/m·K	0.0267	0.0260
	Prandtl Number (Pr). -	0.707	0.709
	Rayleigh Number (Ra_D). -	390.41	44.27
	Nusselt Number (Nu_D). -	2.13	1.81
	Heat Transfer Coefficient (h). W/m²·K	10.64	8.80
	Heat Loss by Natural Convection (Q). W	1.35	0.357
Normal load (video viewing)	Film Temperature (T_f). K	301.43	307.115
	Density – Air (ρ). kg/m³	1.168	1.150
	Thermal Expansion Coefficient (β). K⁻¹	0.003317	0.003256
	Kinematic Viscosity (ν). m²/s	1.60×10^{-5}	1.66×10^{-5}
	Thermal Conductivity (k). W/m·K	0.0263	0.0267
	Prandtl Number (Pr). -	0.708	0.707
	Rayleigh Number (Ra_D). -	227.65	350.99
	Nusselt Number (Nu_D). -	1.95	2.12
	Heat Transfer Coefficient (h). W/m²·K	9.60	10.58
	Heat Loss by Natural Convection (Q). W	0.638	1.187
Maximum load	Film Temperature (T_f). K	304.755	306.80
	Density – Air (ρ). kg/m³	1.159	1.151
	Thermal Expansion Coefficient (β). K⁻¹	0.003281	0.003259
	Kinematic Viscosity (ν). m²/s	1.64×10^{-5}	1.66×10^{-5}
	Thermal Conductivity (k). W/m·K	0.0265	0.0266
	Prandtl Number (Pr). -	0.707	0.707
	Rayleigh Number (Ra_D). -	299.78	343.20
	Nusselt Number (Nu_D). -	2.07	2.11
	Heat Transfer Coefficient (h). W/m²·K	10.25	10.50
	Heat Loss by Natural Convection (Q). W	0.956	1.149

When the Nusselt number is examined in the normal (video watching) and maximum operating environment of the laptop. it is seen that the good refrigerant is a water-methanol mixture.

5. Conclusions

This study investigated the thermal analysis of a laptop heat pipe with R-1234ze refrigerant and water-methanol mixture in the heat pipe under different computer operating conditions. The study shows that the new generation refrigerant R-1234ze can be used in heat pipes without changing the existing heat pipe structure. As an alternative to the traditionally used water-methanol mixture, the new generation R-1234ze refrigerant has shown better performance than the original water-methanol mixture at low temperatures (when the laptop is idling). In the high temperature environment of normal (video watching) and maximum load environment, the performance of R-1234ze refrigerant is very close to the water-methanol mixture, although it is much slower. It is understood that when the wick structure of the laptop's heat pipe is optimized with alternative coolers, full capillarity can be achieved, and therefore it can perform better than traditional fluids at high temperatures. As a result, the selected R-1234ze cooler exhibited excellent compatibility and performance in the notebook heat pipe. In particular, the computer did not shut down at any point during experiments involving extreme temperature loads. This highlights the effectiveness of R-1234ze in maintaining thermal stability.

References

[1] Calame J.P.. Myers R.E.. Binari S.C.. Wood F.N. & Garven M. (2007). Experimental investi-gation of microchannel coolers for the high heat flux thermal management of GaN-on-SiC semiconductor devices. Int. J. Heat Mass Tran. 50(23-24). 4767–4779.

[2] Perpin`a. X.. Jord`a X.. Vellvehi M.. & Altet J. (2011). Hot spot analysis in integrated circuit substrates by laser mirage effect. Appl. Phys. Lett.. 98(16). 164104.

[3] Tavakkoli F.. Ebrahimi S.. Wang S.. & Vafai K. (2016). Analysis of critical thermal issues in 3d integrated circuits. Int. J. Heat Mass Tran. 97. 337–352.

[4] Schmidt R. (2004). Challenges in Electronic Cooling- Opportunities for Thermal Management Techniques - Microprocessor Liquid Cooled Microchannel Heat Sinks. Heat Transfer Engineering. 3-12.

[5] Akkus Y.. Nguyena C.T.. Celebi A.T. & Beşkok. A. (2019). A First Look at the Performance of Nano-Grooved Heat Pipes. A first look at the performance of nano-grooved heat pipes International Journal of Heat and Mass Transfer. 132. 280-287.

[6] Bahiraei M.. & Heshmatian S. (2017). Application of a novel biological nanofluid in a liquid block heat sink for cooling of an electronic processor: Thermal performance and irreversibility considerations. Energy Conversion and Management. 149. 155–167.

[7] Kotcioğlu İ.. Çalışkan S. & Manay E. (2009). Farklı Soğutucular Kullanarak CPU'nun Isı Boruları ile Soğutulması. Isı Bilimi ve Tekniği Dergisi. 29(2). 109-116.

[8] Xu J.. Zhang L.. Xu H.. Zhong J. & Xuan J. (2014). Experimental investigation and visual observation of loop heat pipes with two-layer composite wicks. Int. J. Heat Mass Transf. 72. 378–387.

[9] Liu Z.. Li H.. Chen B.. Yang J. & Liu W. (2012). Operational characteristics of flat type loop heat pipe with biporous wick. Int. J. Therm. Sci. 58. 180–185.

[10] He S.. Liu Z.. Wang D.. Zhao J.. Liu W. & Yang J. (2016). Investigation of the flat disk- shaped LHP with a shared compensation chamber. Appl. Therm. Eng. 104. 139–145.

[11] Xu J.. Wang D.. Hu Z.. Zhang L.i.. Ye L.i. & Zhou Y. (2020). Effect of the working fluid transportation in the copper composite wick on the evaporation efficiency of a flat loop heat pipe. Appl. Therm. Eng. 178. 115515.

[12] Odagiri K. & Nagano H. (2019). Heat transfer characteristics of flat evaporator loop heat pipe under high heat flux condition with different orientations. Appl. Therm. Eng. 153. 828–836.

[13] Maydanik Y.. Chernysheva M. & Vershinin S. (2020). High-capacity loop heat pipe with flat evaporator for efficient cooling systems. J. Thermophys Heat Transfer. 34. 465–475.

[14] Li J.i.. Zhou G.. Tian T. & Li X.. A new cooling strategy for edge computing servers using compact looped heat pipe. Appl. Therm. Eng. 187 (2021) 116599

[15] Liu J.. Zhang Y.. Feng C.. Liu L. & Luan T. (2019). Study of copper chemical-plating modified polyacrylonitrile-based carbon fiber wick applied to compact loop heat pipe. Exp. Therm Fluid Sci. 100. 104–113.

[16] Incropera. F.P.. Dewitt. D.P.. Bergman. T.L.. Lavıne A.S.. Fundamentals of Heat and Mass Transfer. 6th ed. John Wiley & Sons. Inc. USA. 2007.