Isı Bilimi ve Tekniği Dergisi,43, 1, 59-68, 2023
J. of Thermal Science and Technology

ISSN 1300-3615
https://doi.org/10.47480/ isibted.1290697

ANALYSIS OF THERMAL CRACK FORMATION IN WATER-CHARGED AIR-COOLED HEAT EXCHANGERS FOR HEAVY-DUTY VEHICLES

İsmail Hakkı SAVCI
Ford Otosan Flow Performance Durability Department
34885 Sancaktepe, İstanbul, Turkey
isavci@ford.com.tr, ORCID: 0000-0002-7923-6061

(Geliş Tarihi: 27.04.2022, Kabul Tarihi: 12.02.2023)

Abstract: The non-uniform flow distribution at the inlet severely affects the thermal cycling loading of the water-charged air-cooled (WCAC) systems resulting in crack formation after periods and hence leakage in the internal coolant. These cracks are serious since having crucial effects on performance and durability. This work developed a custom thermal fatigue test rig and methodology to precisely determine the crack formation's location and cycle time in WCACs. The test rig was designed to reflect the vehicle's situation by simultaneously controlling the air and waterside of the WCAC continuously. The crack formation occurred by performing tests with different critical cycles on the test rig because a specific cycle was observed, and a thermal cycle profile was created. It was seen that the crack formation in the WCAC can be predicted at the same cycle time and exact location with this test rig compared to the vehicle tests. Moreover, the total cost, time, and man-hours per test decreased by 80 %,75 %, and 60, % respectively, compared to traditional vehicle tests. Subsequently, the modified WCAC design was proposed to prevent non-uniform flow distribution at the inlet of the WCAC. The thermal fatigue tests of the modified WCAC design were tested in a developed test rig for stressful operating conditions. The results showed that the modified WCAC design is more robust than the old design. There was no crack formation in the modified WCAC design under various stressful operating conditions.
Keywords: WCAC, Heat-exchanger, Thermal Fatigue, Thermal Cracking, Automotive Applications

AĞIR HİZMET ARAÇLARI İÇİN SU ŞARJLI HAVA SOĞUTMALI ISI DEĞİŞTİRİCİLERİNDE ISIL ÇATLAK OLUŞUMUNUN ANALİZİ

Özet: Girişteki muntazam olmayan akış dağılımı, su şarjlı hava soğutmalı (WCAC) sistemlerin termal döngü yüklemesini ciddi şekilde etkiler, bu da belirli çevrimlerden sonra çatlak oluşumuna ve dolayısıyla dahili soğutucuda sızıntıya neden olur. Bu çatlaklar, performans ve dayanıklılık üzerinde önemli etkilere sahip olduğundan ciddidir. Bu çalışmayla, WCAC'lerde çatlak oluşumunun yerini ve döngü süresini kesin olarak belirlemek için özel bir termal yorulma test donanımı ve metodolojisi geliştirildi. Test teçhizatı, WCAC'ın hava ve su tarafını aynı anda sürekli olarak kontrol ederek aracın durumunu yansıtacak şekilde tasarlanmıştır. Test teçhizatı üzerinde farklı kritik çevrimlerle testler yapılarak belirli çevrim sonucunda oluşam çatlak gözlemlenmiş ve termal çevrim profili oluşturulmuştur. Bu test düzeneği ile WCAC içerisindeki çatlak oluşumunun araç testlerine göre aynı çevrim süresinde ve tam lokasyonda tahmin edilebildiği görülmüştür. Ayrıca, geleneksel araç testlerine kıyasla test başına toplam maliyet, zaman ve adam-saat sırasıyla %80, %75 ve %60 azaldı. Daha sonra, WCAC girişinde üniform olmayan akış dağılımınını önleyen için değiştirilmiş WCAC tasarımı geliştirildi. Modifiye edilmiş WCAC tasarımının termal yorulma testleri, zorlu çalışma koşulları için geliştirilmiş bir test profili ile test riginde test edilmiştir. Sonuçlar, değiştirilmiş WCAC tasarımının eski tasarıma göre daha sağlam olduğunu göstermiştir. Çeşitli zorlu çalışma koşulları altında değiştirilmiş WCAC tasarımında herhangi bir çatlak oluşumu olmamıştır.
Anahtar Kelimler: WCAC, Eşanjör, Termal Yorulma, Termal Çatlama, Otomotiv Uygulamaları

NOMENCLATURE

Abbreviations

EGR	Engine Gas Recirculation
ACAC	Air Charged Air Cooler
WCAC	Water Charged Air Cooler
MAE	Mean Absolute Error

Subscripts

u	Velocity Related Value
T	Temperature
BC	Boundary Condition

Symbols

p	Pressure
ε	Average Strain Magnitude
M	Mass Flow Meter
t	Non-dimensional Time

INTRODUCTION

Although electric vehicles have emerged in daily life, motor vehicles are still the primary form of transportation in the world (Panchal et al., 2018). However, the environmental and social damages of exhaust emissions have reached critical degrees, resulting in stringent regulations by policymakers. Consequently, motor vehicle manufacturers have researched alternative solutions to release exhaust emission levels. Subasi et al. (2017) reported that the transportation sector, including rail, aviation, shipping, and road transportation is responsible for 30 % of global carbon dioxide emissions. One way to reduce exhaust emissions is by improving the efficiency of the engine cooling system. The efficient cooling produces lower smoke (particulate) emissions due to higher density and the air-fuel ratio (Edara et al., 2019). The purpose of the engine cooling system is to prevent the vehicle engine from overheating by keeping the engine at optimum operating temperature. Various novel architectures of cooling systems have been developed to improve the cooling system's efficiency and meet new emission regulations. The Water Charged Air Cooler (WCAC) and the Air Charged Air Cooler (ACAC) systems can be mentioned. These systems regulate the pressure and distribution of the exhaust gas at the inlet of the cooling loop. In ACAC systems, the primary and secondary fluids are air, whereas the primary fluid is air, and the secondary fluid is water in WCAC systems. WCACs are heat exchangers facilitating heat transfer between two fluids at different temperatures. WCACs use lower charge air temperatures than ACACs, which leads to lower temperatures for combustion gases and, therefore, produces lower NOx emissions (Lujan et al., 2016).

Furthermore, the WCAC improves the engine response in transient conditions by reducing the charge air volume between the compressor and the engine. Besides, the WCAC increases the engine's durability by reducing the temperature in the cylinders and the exhaust system (Broatch et al., 2008). The WCAC is located between the turbocharger and the engine air inlet manifold in heavy-duty engines. The WCAC and turbocharger are part of a high-tech induction system that increases engine combustion efficiency. The ambient air is compressed and heated in the turbocharger before it enters the WCAC. The compressed and warm air directs to the WCAC and is cooled by the cold ambient air flowing across the cooler fins. Since the cold air is denser than the warm air, the volumetric air rate entering the engine increases. Therefore, the power and engine efficiency improvements and fuel consumption and exhaust emissions decrease (Burgold et al.., 2012); (Arikan et al., 2008); (Savci et al., 2022). WCACs are operated in highly stressful environments, and consequently, the parts of the WCAC must be resistant to thermal load and vibration. Otherwise, system components may be damaged over time due to thermal fatigue (Torregrosa et al., 2008). The damage in the system reduces the boost pressure and increases the intake manifold temperature. Hence, the engine provides lower power and higher emission levels than the design values (Joshi et al., 2009); (Wang et al., 2011).

In the literature, many studies reported that the non-uniform flow distribution at the inlet of heat exchangers might escalate wall heat conduction longitudinally. Therefore, the non-uniform flow distribution at the inlet of heat exchangers may be one of the responsible mechanisms of thermal fatigue cracks in the device (Yaici et al.., 2014); (Demirkesen et al., 2020); (Holland et al., 2015); (Salmon et al., 2017); (Vashahi et al., 2014); (Iwahori et al., 2013). There are several methods to determine the location of the thermal cracks in engine cooling systems. These models can be summarised in three chapters. First, one is to monitor sensor data, fuse data from the sensors, and predict cracks; the second is to develop a test rig and repeat the cracks into experimental studies. The third one is to create finite element methods. Joshi et al. (2009) developed a model to diagnose a fault in the intercooler of different engines. The authors monitored the status of the WCAC intercooler by analyzing the intake manifold temperature signal. They blocked the air flowing over the intercooler by varying degrees for different engine temperatures, pressure, and torque conditions. It was found that the model successfully predicted the failure of the intercooler. Haider et al. (2015) designed a test rig to investigate thermal stress in aluminum-brazed plate-fin heat exchangers due to the transient temperature profiles. The researchers designed a test rig to reflect extreme operating conditions calculated by developing a finite element method-based model. The results showed that the location of maximum stress in the finite element method model matched the cracks observed in the heat exchanger. In another study, Iwahori et al. (2013) developed a finite element model of a WCAC intercooler using the homogenization method.

Usman and Khan (2008) investigated the failure reasons of heat exchanger tubes experimentally using a tube material ASTM A213 grade T11. They found that the cracks across the tube axis are caused by thermal fatigue due to temperature variations causing stresses in the tube wall. They reported that the cyclic heating and cooling caused thermal fatigue, which resulted in circumferential cracks. They also said that longitudinal cracks occurred due to exposure to higher-than-permissible temperatures. In a recent study, Ali et al.

(2020) reviewed the common failures in heat exchangers due to elevated temperature values. They concluded that thermal fatigues are one of the leading causes of failures in heat exchangers. They stated that thermal fatigue could be attributed to the oscillation in temperature because of poor water circulation. Also, they reported that thermal fatigue due to a rise in temperature or localized overheating caused transverse cracking in serpentines. They concluded that design modifications are needed to prevent cracks due to thermal fatigue. Since WCACs are heat exchangers, the design of the WCAC is essential since it is exposed to high thermal stress rates and therefore has a high possibility of crack formation (Ali et al., 2020).

Consequently, several researchers attempted to modify the design of the intercoolers to prevent the thermal crack formation and increase the intercooler's lifetime. In a study by O'Connor and Trauger (1990), the effect of turbocharger outlet temperature on the durability of the charge air cooler was examined experimentally. They found that the elevated turbocharger outlet temperature resulted in higher strain magnitude and strain cycling of the charge air cooler. The design modifications in charge air coolers can help reduce the strain magnitudes. In another study, Kolb et al. (1998) proposed using a resilient tube to header joints and grommeted seals between the tubes and headers in a charger air cooler to eliminate the high stresses in the device and consequently provide longer equipment life. They reported that the new charge air cooler design with the mentioned modifications did not show any leakage on the surface of the charge air cooler during vehicle tests. Mezher et al. (2013) analyzed the four-cylinder diesel engine to present the reflection characteristics of the intake of the WCAC intercooler. The results showed that the pipeline length between the intake manifold and intercooler has an essential effect on the system's thermal efficiency.

The above brief literature review indicates some studies to analyze crack formation due to thermal stress in heat exchangers. Furthermore, the literature review reveals that the non-uniform flow distribution at the inlet of heat exchangers is the dominant parameter of crack formation (Canyurt et al., 2022). However, there are limited studies to analyze crack formation due to thermal fatigue in WCAC intercoolers. The current study aims to design and validate an experimental setup to determine the crack formation's location and cycle time in WCAC intercoolers. Accordingly, the pre-existing WCAC intercooler design was modified to prevent crack formation due to thermal fatigue. The custom experimental setup was validated with vehicle test data. The proposed experimental setup can be an alternative to expensive and time-consuming traditional vehicle tests.

MATERIALS AND METHODS

Water-charged air-cooled (WCAC) are specific heat exchangers used in particularly stressful conditions, such as internal combustion engines with turbochargers. When the turbocharger compresses the air, it is heated simultaneously, causing its density to decrease by cooling the combustion air with a charge air cooler before it is sent to the engine, the density of the air increases, allowing more air to enter the engine, increasing engine power and efficiency. The cooler in the engine is located between the turbocharger and the engine air intake manifold.
The cooler and turbocharger are part of a high-tech induction system that improves combustion efficiency. The turbocharger uses ambient air to compress it before entering the cooler. The ambient air flowing through the cooling fins cools the compressed air passing through the cooler. Cooled air is denser than warm air. Thus, when flowing to the intake side of the engine, the increased density increases horsepower, saves fuel, and reduces emissions. Figure 1 shows the WCAC cooling and air circuits schematically.

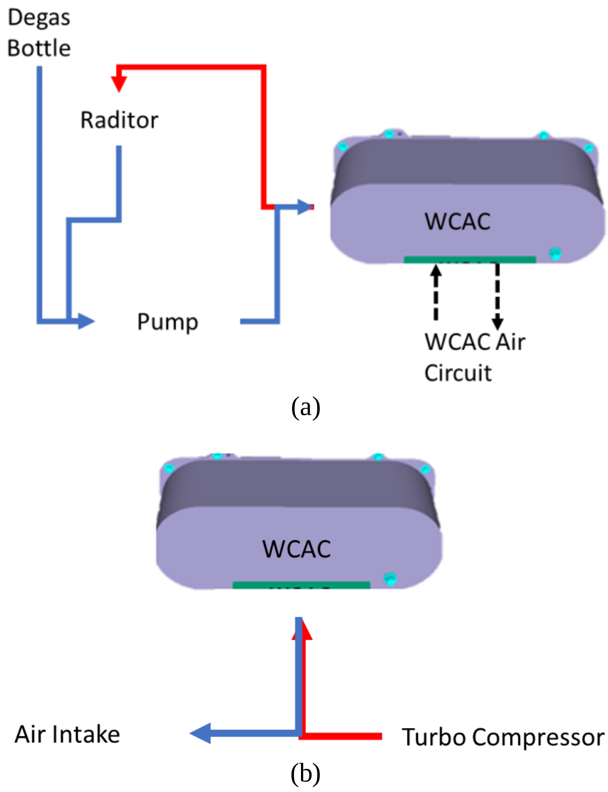


Figure 1. WCAC cooling circuit, (a) coolant circuit, (b) air circuit.

Integrating WCAC into the intake manifold is an ideal design solution that offers the best engine performance. The detailed schematic of the cooling part of the WCAC system can be shown in Figure 2. The main components of the cooling part are the fin, header, sidebar, and parting sheets. These components form a compact plate heat exchanger.

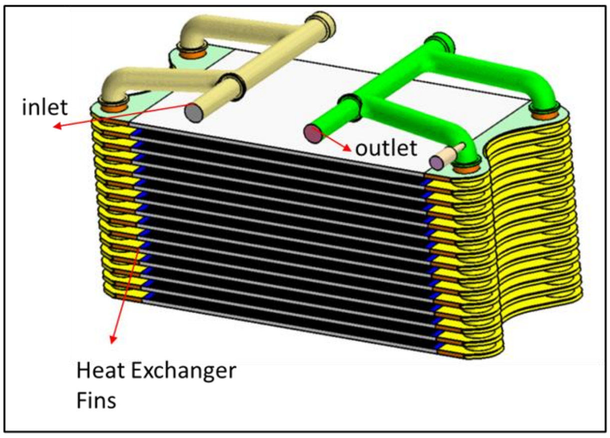


Figure 2. WCAC Cooling Part

Figure 3 shows the sensor instrumentation on the WCAC. The strain gauge is instrumented right side of the WCAC where the cracks occur.

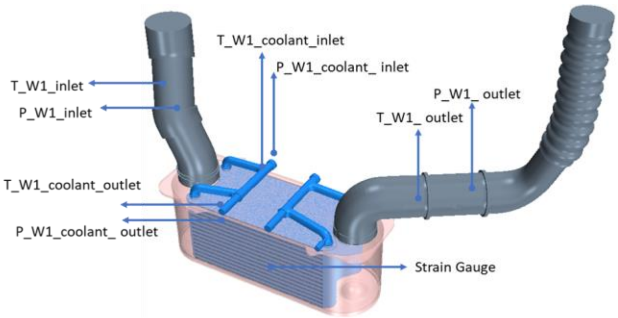


Figure 3. Sensor Instrumentations

Figure 4 shows the temperature and pressure instrumentations on WCAC. The DSpace microautobox is used to control valves and the burner system. Due to the high temperature of the valve, the valve should be a cooling system, so the EGR valve is selected for this test bench. Sensor measurement is done by national instrument measurement cards.

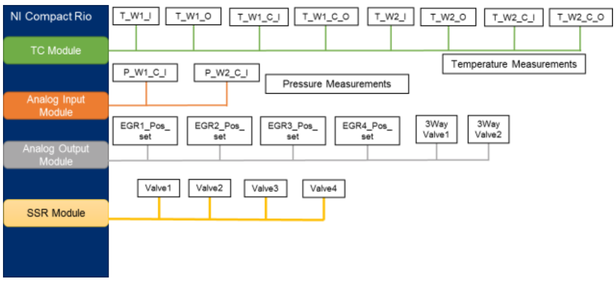


Figure 4. Control Schematic of the WCAC Test Bench

During the vehicle tests on the heavy-duty truck engine, it was observed that the WCAC cooling part cracked due to thermal gradients in specific cycles under continuous thermal load. These cracks caused leaks in the intercooler. Figure 5 presents the average strain magnitude (ε) of the vehicle's durability test for four cycles of stressful and average conditions. It was observed that the crack formation started in the WCAC cooling part for the stressful operating condition. In contrast, there was no evidence of a crack for the average operating condition for four cycles. The strain data in Figure 5 was used to construct the custom test rig to observe whether the test rig can simulate vehicle tests accurately. Cycle 1, cycle 2, cycle 3, and cycle 4 represent the tests applied to temperature profiles specified in Figure 6. The strain values are varied at 12 percent according to the average values.

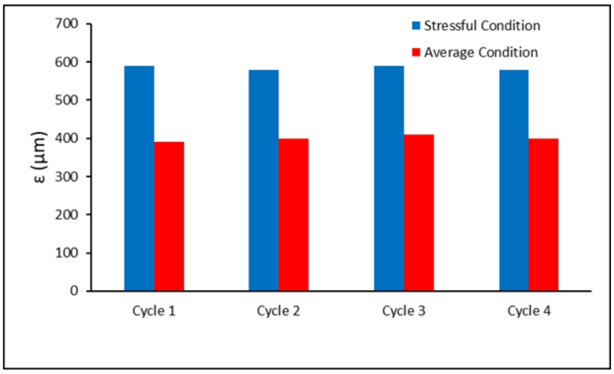
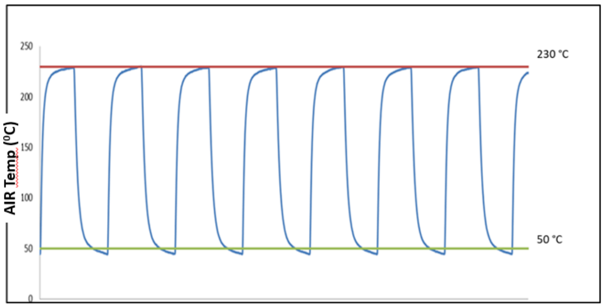
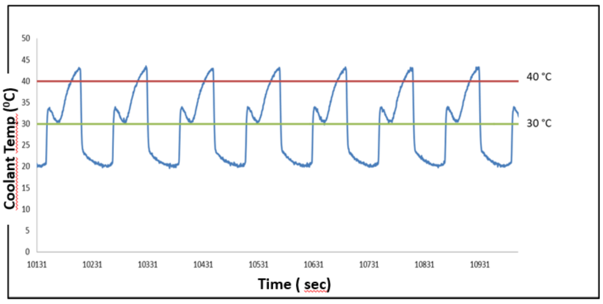


Figure 5. Average strain magnitude measurements for two different conditions from the vehicle test data

Furthermore, the temperature profiles of air and coolant sides were obtained for the stressful condition vehicle tests to reveal the maximum and minimum temperatures, in other words, boundary conditions of vehicle tests under variable thermal load to verify the custom test rig; please see Figures 6(a)-(b).



(a)



(b)

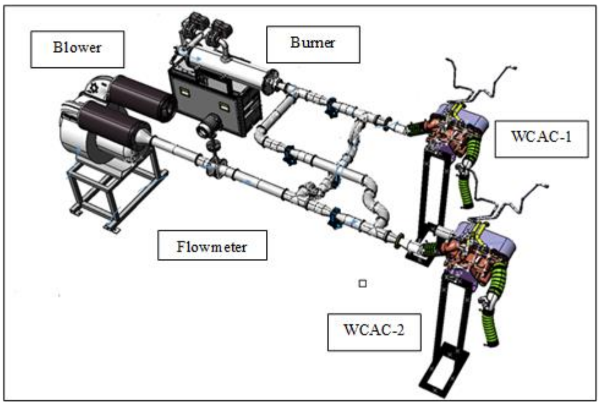
Figure 6. Temperature profile, (a) Airside, (b) Coolant side.

The boundary conditions of the test profile can be found in table 1. Figure 6a. red line represent BC1, green line represents BC2. Figure 6b red line represents BC3, and the green line represents BC4.

Table 1. Test parameters

		T	Unit	M	Unit
Hot Air	BC1	230	^0C	1000	kg/h
Cold Air	BC2	50	^0C	500	kg/h
Hot Water	BC3	40	^0C	1000	l/h
Cold Water	BC4	30	^0C	900	l/h

As mentioned above, the most effective way to find the main reasons for WCAC cracks is by performing vehicle tests. The vehicle test includes thermal fatigue tests with air and coolant flow cycles. However, the vehicle test could be more cost-effective due to many tests and parts requirements and maintenance of test types of equipment. Therefore, a custom test rig is designed to simulate the cooling mechanism of the engine completely. Figures 7(a)-(b) demonstrate the test rig's schematic drawing and photograph, respectively.



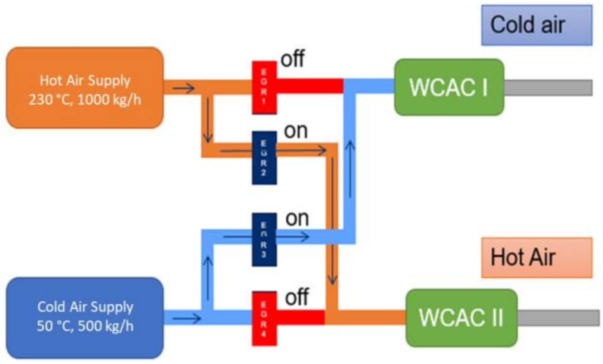
(a)

(b)

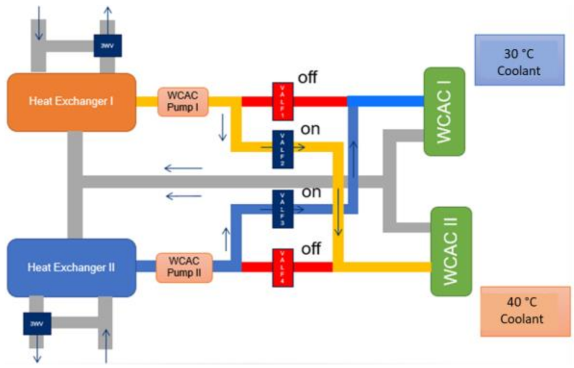
Figure 7. The WCAC test rig, (a) Schematic Drawing, (b) Photograph.

The test rig consists blower system for cold air supply, an AC motor with an inverter speed controller of 22 kW, a burner system with 400 kW which works with natural gas, the mass flowmeter (40-1500kg/h), a data acquisition system (national instruments) for measurement and data recording, solenoid valves to control coolant flow, EGR valves to control airflow and a three-way valve with a proportional controller to control the temperature of the coolant. As a result, two identical WCAC coolers can be tested simultaneously in the test rig, as shown in Figure 7 (a).

The test rig has two synchronic cycles: air and coolant cycles. These two loops are driven by four different EGR valves controlled by the data acquisition system. As can be seen from Figures. 8(a-b), WCAC-1 and WCAC-2 return the coolant with two different WCAC pumps. The positions of the valves are switched to direct the flow to the system at the desired condition. The flow enters the test bench from two entrances, as seen in Figures 8(a)-(b) below, and reaches the EGRs. After that, the flow goes to WCAC-1 or WCAC-2 according to the path assigned. The positions of EGRs are controlled for the cold airpath and hot air path in different ways. The cold air source is a blower, whereas the burner supplies the hot air to the test chamber.



(a)



(b)

Figure 8. The cycle diagram of the test rig, (a) air, (b) coolant.

The tests were conducted three times for two identical WCACs in cold flow and hot flow conditions separately to ensure the repeatability of tests. Therefore, experimental tests are always subject to some uncertainty. The uncertainty values for the measured parameters are obtained from sensor data sheets and are given in Table 2.

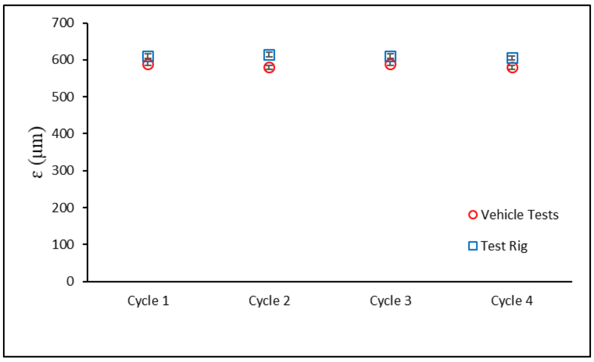
Table 2. Uncertainty values for the measured parameters

Measured parameter	The instrument	Uncertainty
Airflow rate	Mass flowmeter	±0.00001kg/s
Coolant flow rate	Mass flowmeter	±0.00001kg/s
The temperature of the air	K Thermocouple	±0.24 K

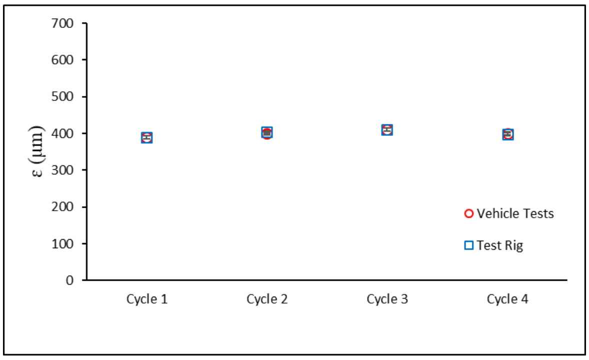
The temperature of the coolant	K Thermocouple	±0.24 K
Pressure	Gauge Pressure	±0.01 kPa
Strain	Strain gauge	±1 %

RESULTS AND DISCUSSION

Figure 9 (a) and (b) demonstrate the strain measurements on the WCAC cooling part with vehicle tests and develop a custom test rig for stressful and average conditions. After the development of the test rig, the tests were conductedevelopfy the measurement of the rig compared to vehicle tests. It can be seen that the strain measurements taken from the test rig are highly correlated with vehicle tests for four different cycles and two different conditions. For example, the Mean Absolute Error (MAE) of the two measurements at the stressful condition tests is in the range of 3.39 - 6.03 %, whereas it is 0.2 – 0.5 % at the average condition tests.



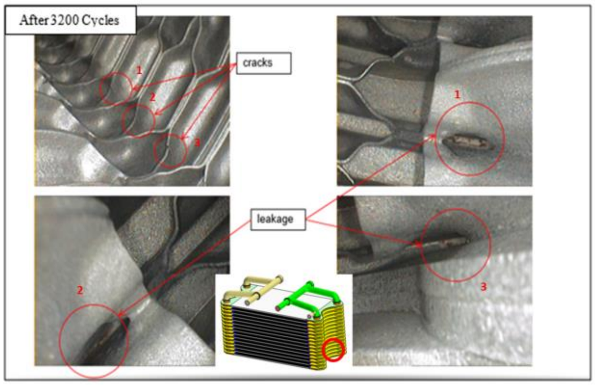
(a)



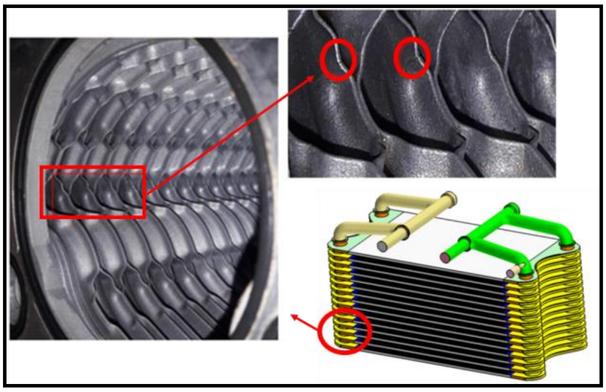
(b)

Figure 9. Verification of the test rig with vehicle tests for four different cycles, (a) Stressful Condition, (b) Average Condition

Subsequently, four critical cycles were determined and organized by engine heating-cooling data to characterize the same engine working conditions. At the end of each cycle, the WCACs were inspected periodically to detect crack formation using an endoscopic camera. According to the vehicle tests, the WCAC control cycle plan was defined with the four critical cycles. These are the 120th cycle, 240th cycle, 550th cycle, and 3200th cycle. The first inspection of the WCACs was conducted at the end of the 120th cycle. It was seen that the corroded regions that have a crack formation possibility could be detected even at the lowest cycle. When the WCACs were inspected at the second cycle (240th cycle), it was observed that the corroded regions enlarged, and the leakage from the intercooler started. The WCACs damage was detected in the 240th cycle compared to the 120th cycle from the erosion point of view. The third inspection was performed at the end of the 550th cycle, and there was still no crack, but the corroded regions became quite large. Therefore, the test was continued to the end of the 3200th cycle. The visualization study showed deep crack regions, and the heavy coolant leakage on the metal existed at the end of the 3200th cycle. On the blades, there were cavitated regions, and the trails were widening. The leak's location was detected at the last stacked plate in the series of connection plates. The crack and leak detection images at the end of the 3200th cycle control are presented in Figures 10 (a)-(b).



(a)



(b)

Figure 10. The crack and leak detection images at the end of the 3200th cycle control, (a) left side of WCAC heat exchanger, (b) front right side of WCAC heat exchanger

At the end of the tests, the first crack formation was seen when the tests reached the 3200th cycle; in this cycle, the cracks were very sharp and deep such as 8 mm in length with 3 mm width and 5 mm depth. Cracks were observed in Figure 11 by using SEM (scanning electron microscope). The amount of leakage was high such as %5 percent, so WCAC became unusable. According to the test rig results, the cycle time, strain magnitudes, and crack location are identical in the vehicle tests and the test equipment.

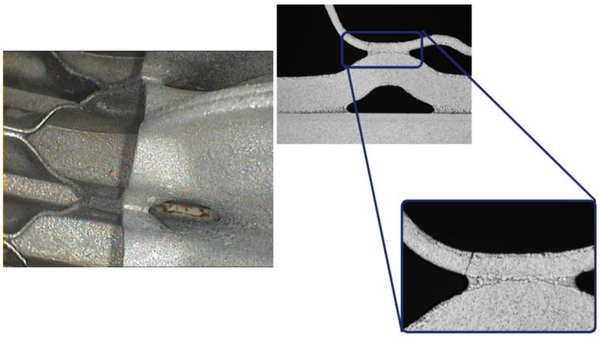


Figure 11. Cracks at the connection of the coolant and air (5mm depth, 10 mm length with 3 mm width)

Although vehicle tests are the most reliable method to detect WCAC cracks, the inconvenience, and high cost led us to investigate other techniques, as mentioned before (Moreira et al., 2019). Table 2 presents an infrastructure, operation, and engineering costs comparison between the two methods. In Table 2, the infrastructure cost has been taken from the refs. (Ahlin et al., 2004); (National2021); (Hertz2021) the engineering cost values have been obtained from the ref. (glassdoor2021). Moreover, the operational cost (electricity) has been taken from the Invest2021. On the other hand, the test duration comparison of the two methods is presented in Table 3. As can be observed from Tables 2 and 3, the test rig is a more cost-effective method compared to vehicle tests.

Table 3. Cost comparison of two methods

Cost Unit	Vehicle Tests	Test rig
Infrastructure ($) (VehicleRent-TestRigCost)	60000	10000
EngineeringCost($/month)	7500	1000
OperationalCost ($/month)	10000	2000
Total ($+$/month)	100000	16000

Table 4. Test duration comparison of two methods

Item	Vehicle Tests	Test rig
Time (days)	60	15
Man Hours (hour/test)	4	1.5

Consequently, the design of the WCAC part was modified by extending the length of the inlet tubes seven times the length of the diameter of the pipes to prevent non-uniform flow distribution at the inlet of the WCAC. This modification was chosen according to the literature survey presented in the introduction. The tests of the modified WCACs were conducted using the developed test rig for various stressful conditions. As a result, the modified WCAC part was found to be more robust than the old design, and there was no evidence of crack formation.

CONCLUSIONS

This study developed a specialized thermal fatigue testing rig to determine crack formation's location and cycle time in WCAC parts as an alternative to vehicle testing. Test rig data were validated with differences of up to 5 percent compared to strain measurement, position, and thermal stress data from vehicle tests. Also, crack formation in WCACs was examined periodically with an endoscopic camera after each test for different critical cycles in the test setup. It has been observed that crack formation in WCACs differs by no more than 10 percent from the cycle time in the test rigs and the vehicle's cycle time. The location of the refraction obtained from the special test equipment developed is only 1 cm different from that obtained from the vehicle tests. In addition, the cost and test time between the two methods were compared, and it was seen that the test equipment method was 80% cost-effective compared to vehicle tests.

The literature survey conducted in this study revealed that the non-uniform flow distribution at the inlet of heat exchangers is the dominant parameter of crack formation. Therefore, the WCAC system was re-designed by increasing the length of the inlet tubes seven times the diameter of the pipes to prevent non-uniform flow distribution at the inlet. Finally, the modified WCAC system was tested under stressful operating conditions through the developed custom test rig. The results showed that the WCAC is more robust than the old design, and there was no evidence of crack formation until the 10000 cycles, even under stressful operating conditions.

ACKNOWLEDGMENT

The author would like to thank Aydın Ayyıldız and Hakan Gokoglu for the technical support of this research.

REFERENCES

Ahlin, K., Granlund, J., and Lindstrom, F., 2004, Comparing road profiles with vehicle perceived roughness, *International Journal of Vehicle Design*, 36(2), 270-286.

Ali, M., Ul-Hamid, A., Alhems, L. M., and Saeed, A., 2020, Review of common failures in heat exchangers– Part I: Mechanical and elevated temperature failures, *Engineering Failure Analysis*, 109, 104396.

Arıkan, K. B., 2008, *Identification of handling models for road vehicles*, Ph.D. Thesis, Middle East Technical University, Ankara, Turkey.

Broatch, A., Luján, J. M., Serrano, J. R., and Pla, B., 2008, A procedure to reduce pollutant gases from Diesel combustion during the European MVEG-A cycle by using electrical intake air heaters. *Fuel*, 87(12), 2760-2778.

Burgold, S., Galland, J. P., Ferlay, B., and Odillard, L., 2012, Modular Water Charge Air Cooling for Combustion Engines. *MTZ worldwide*, 73(11), 26-31. doi: https://doi.org/10.1007/s38313-012-0237-z.

Canyurt, T. G., Ergin, S., Zeren, H. B., Savcı I. H., 2022, Experimental and numerical investigation on the urea-deposit formation at different severities in selective catalytic reduction systems, *Applied Thermal Engineering*, 214, 118884 .
doi:https://doi.org/10.1016/j.applthermaleng.2022.118884.

Demirkesen, C., Colak, U., Savci, I. H., and Zeren, H. B., 2020, Experimental and Numerical Investigation of Air Flow Motion in Cylinder of Heavy Duty Diesel Engines', *Journal of Applied Fluid Mechanics*, 13(2), 537-547. doi: 10.29252/jafm.13.02.30369

Edara, G., Murthy, Y. S., Nayar, J., Ramesh, M., and Srinivas, P., 2019, Combustion analysis of modified light-duty diesel engine under high-pressure split injections with cooled EGR. *Engineering Science and Technology, an International Journal*, 22(3), 966-978. doi: https://doi.org/10.1016/j.jestch.2019.01.013

Internet, 2021, Hertz car, *car rental cost table*, https://www.hertz.com/p/car-rental.

Holland, B., McKinley, T., and Storkman, B., 2015, Modeling Approach to Estimate EGR Cooler Thermal Fatigue Life, *SAE International Journal of Engines*, 8(4), 1724-1732.
doi: https://doi.org/10.4271/2015-01-1654.

Hoseinzadeh, S., and Heyns, P. S., 2020, Thermo-structural fatigue and lifetime analysis of a power plant's heat exchanger as a feedwater heater, *Engineering Failure Analysis*, 113, 104548. doi: https://doi.org/10.1016/j.engfailanal.2020.104548.

Internet, 2022, Investment support and promotion agency of the Republic of Turkey, *Electricity Cost*, http://www.invest.gov.tr.

Iwahori, K., Ohno, N., Okumura, D., and Muraki, T., 2013, The Large Scale Finite Element Analysis of a Charge Air Cooler Using a Homogenization Method. *SAE Technical Paper*, 01-1212.

Joshi, A. A., James, S., Meckl, P., King, G., and Jennings, K., 2009, Assessment of charge-air cooler health in diesel engines using nonlinear time series analysis of intake manifold temperature. *Journal of dynamic systems, measurement and control*, 131(4), 041009-041020.
doi: https://doi.org/10.1115/1.3023142.

Kolb, J., Zhao, M., Lambert, M., and JuGer, J., 1998, Long Life, Heavy Duty, Air-to-Air Charge Air Cooler. *SAE transactions*, 107(2), 182-214.

Kuehnel, W., Weise, S., Krueger, U., and Sekler, H., 2005, The Validation Process- One Key Element of Reliability Management. *SAE Technical Paper*, https://doi.org/10.4271/2005-01-1778.

Laurent, M., Estevez, R., Fabrègue, D., and Ayax, E., 2016, Thermomechanical fatigue life prediction of 316L compact heat exchanger. *Engineering Failure Analysis*, 68, 138-149.
doi: https://doi.org/10.1016/j.engfailanal.2016.06.003.

Luján, J. M., Climent, H., Dolz, V., Moratal, A., Borges-Alejo, J., and Soukeur, Z., 2016, The potential of exhaust heat recovery for intake charge heating in a diesel engine transient operation at cold conditions. *Applied Thermal Engineering*, 105, 501-508.
doi:https://doi.org/10.1016/j.applthermaleng.2016.03.028.

Mezher, H., Migaud, J., and Raimbault, V., 2013, Optimized Air Intake for a Turbocharged Engine Taking into Account Water-Cooled Charge Air Cooler Reflective Properties for Acoustic Tuning. *SAE Technical Paper*, 1, 0575-0587.
doi: https://doi.org/10.4271/2013-01-0575.

Moreira, T.A., Colmanetti, A.R.A., and Tibiriçá, C.B., 2019, Heat transfer coefficient: a review of measurement techniques. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 41, 264.
doi: https://doi.org/10.1007/s40430-019-1763-2.

Internet, 2022, National Instruments, *Technical Specifications*, https://www.ni.com.

O'Connor, T. W., and Trauger, P. E., 1990, The Impact of Elevated Turbocharger Outlet Conditions on Charge Air Cooler Durability. *SAE Technical Paper, Truck and Bus Meeting, and Exposition*, Detroit, Michigan, USA.

Internet, 2021, Glass Door , *Salaries*, https://www.glassdoor.com/Salary/Ford-Motor-Company-Cost-Engineer-Salaries-E263_D_KO19,32.htm .

Panchal, C., Stegen, S., and Lu, J., 2018, Review of the static and dynamic wireless electric vehicle charging system. *Engineering Science and Technology, an International Journal*, 21(5), 922-937.
doi: https://doi.org/10.1016/j.jestch.2018.06.015.

Ren, P., Li, Z., Wu, J., Guo, Y., and Li, W., 2017, Failure analysis of blots for diesel engine intercooler. *In Journal of Physics: Conference Series,* 842 (1), 012063-012071.
doi: https://doi.org/10.1088/1742-6596/842/1/012063.

Salmon, P., Könözsy, L., Temple, C., and Grove, S., 2017, Numerical investigation on various heat exchanger performances to determine an optimum configuration for charge air cooler, oil, and water radiators in F1 sidepods. *Applied Thermal Engineering,* 117,235-244.
doi:https://doi.org/10.1016/j.applthermaleng.2017.02.026.

Savci, I. H., Gul, M. Z., 2022, A methodology to assess mixer performance for selective catalyst reduction application in hot air gas burner. A*lexandria Engineering Journal,* 61(9), 6621-6633.
doi: https://doi.org/10.1016/j.aej.2021.12.011

Subasi, A., 2017, *Numerical and experimental investigation of boundary layer transition with active and passive flow control methods*. Ph.D. Thesis. Istanbul Technical University, Istanbul, Turkey.

Torregrosa, A.J., Broatch, A., Olmeda, P. and Romero, C. 2008, Assessment of the influence of different cooling system configurations on engine warm-up, emissions, and fuel consumption. *International Journal of Automotive Technology*, 9(4), 447-458.
doi: https://doi.org/10.1007/s12239−008−0054−1.

Usman, A., and Khan, A. N. 2008, Failure analysis of heat exchanger tubes. *Engineering Failure Analysis*, 15(1-2), 118-128.
doi: https://doi.org/10.1016/j.engfailanal.2006.11.051.

Vashahi, F., Lee, M., Kim, J., Kim, D., and Baek, B. J., 2014, A numerical study on the thermal and strain characteristics of EGR cooler. *International Journal of Control and Automation,* 7(7), 241-252.
doi: https://doi.org/10.14257/ijca.2014.7.7.20.

Wang, C. C., Yang, K. S., Tsai, J. S., and Chen, Y., 2011, Characteristics of flow distribution in compact parallel-flow heat exchangers, part I: typical inlet header. *Applied Thermal Engineering,* 31(16), 3226-3234.
doi:https://doi.org/10.1016/j.applthermaleng.2011.06.004.

Yaïci, W., Ghorab, M., and Entchev, E., 2014, 3D CFD analysis of the effect of inlet air flow maldistribution on the fluid flow and heat transfer performances of plate-fin-and-tube laminar heat exchangers. *International Journal of Heat and Mass Transfer,* 74, 490-500.
doi:https://doi.org/10.1016/j.ijheatmasstransfer.2014.03.03.

Yu, C., Qin, S., Chai, B., Huang, S., and Liu, Y., 2019, The Effect of Compressible Flow on Heat Transfer Performance of Heat Exchanger by Computational Fluid Dynamics (CFD) Simulation. *Entropy*, 21(9), 829.
doi: https://doi.org/10.3390/e21090829.