RESEARCH ON ENHANCING SAFETY OF USING R290 REFRIGERANT IN FUTURE XEVS

Kunihiko HAYASHI *, Yoshiaki MIYAZATO *, Tomoki SHIMIZU **
* Toyota Motor Corporation, 1200 Mishuku, Susono, Shizuoka, 410-1193, Japan
**SOKEN Inc., 500-20 Minamiyama, Komenoki-cho, Nisshin, Aichi, 470-0111, Japan

ABSTRACT

In response to global warming and environmental concerns, countries striving to achieve carbon neutrality are implementing regulations such as fuel economy standards and potentially restrictions on PFAS. Concurrently, the automotive industry is striving to improve range in electric vehicles. Specifically, electric vehicles are increasingly being equipped with heat pumps to enhance fuel economy and extend driving range during winter heating. In this study, we conducted preliminary safety verification of R290 propane refrigerant through both CFD simulations and actual vehicle testing.

Key Word: Refrigerant leakage, R290 , Propane , Natural Refrigerant

INTRODUCTION

In response to global warming, environmental issues, and carbon neutrality initiatives, regulations on fuel economy and CO_2 emissions are being implemented in various countries. Consequently, the automotive industry faces an urgent need to improve fuel economy and range of electric vehicles. In particular, electric vehicles are increasingly equipped with heat pumps to improve range in winter, and new refrigerants suitable for heat pumps are being investigated to further improve efficiency [1]. However, in anticipation of potential upcoming EU regulations on PFAS, it is necessary to develop a diverse range of refrigerants including natural refrigerant shown in table 1.

R290 (propane), a natural refrigerant that is not classified as a PFAS and offers excellent heating/cooling performance, is currently being approved for home appliance and commercial applications [2][3]. It is also undergoing standardization and safety reviews for automotive use, as shown in table 1 [4]. However, it has not yet been permitted for use in automobiles, and no standards have been established to date.

Table 1 Natural refrigerant candidates

	Refrigerant	EU PFAS definition	Performance Heating	Performance Cooling	Standard (for Auto)	Flammability
Current	R1234yf	× (Subject to PFAS)	○	○	○	A2L
Natural Refrigerant	CO_2 (R744)	✓(non PFAS)	○+	○−	○	−
	Propane (R290)	✓(non PFAS)	○+	○+	N/A	A3

In this study, we conducted a safety assessment of the flammability of R290 refrigerant using actual vehicles and CFD, assuming future standardization.

Regarding the standardization of R290 refrigerant for automobiles, discussions are currently underway within the Society of Automotive Engineers (SAE), following the submission of a SNAP application to U.S. authorities last year. Through this research, we aim to contribute to these standardization efforts and promote safe system designs with fail-safe features, as outlined in ISO26262. This study focuses on flammable mixtures among risk factors showed in Figure 1 and verifies safety in the event of a refrigerant leak.

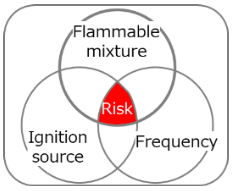


Fig. 1 Risk factors

SCENARIOS UNDER CONSIDERATION

In vehicles equipped with underhood refrigeration systems, potential refrigerant gas leak paths include: (1) direct leakage to the outside of the vehicle, (2) gas intrusion into the passenger cabin, and (3) leakage into the passenger cabin or outside via the cooling loop, as shown in Figure 2. Based on a risk assessment study, SAE has identified leakage occurring while the vehicle is parked in a small garage as the worst-case condition. This study is conducted under those conditions.

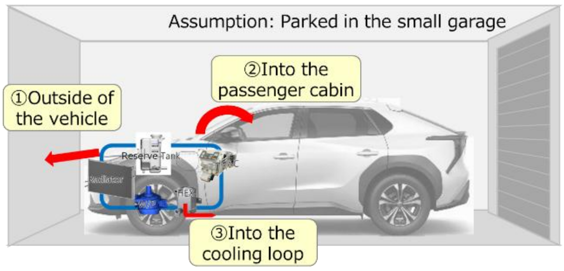


Fig. 2 Possible gas leak route

GARAGE LEAK VERIFICATION

Using CFD analysis and a physical vehicle, we evaluated gas leakage in a small garage shown in Figure 3. We also simultaneously verified the effect of operating the vehicle's radiator e-Fan as a mitigation measure to reduce gas concentration. The test vehicle was a Toyota bZ4X BEV. A 3mm wide slit, modeled after a garage shutter, was installed at the rear of the garage to simulate ventilation to the outside.

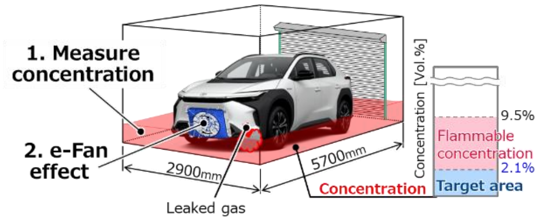


Fig. 3 Environmental condition

The lower flammable limit (LFL) of R290 is 2.1 vol%, and this value was used as the safety threshold for verification. In addition to CFD analysis, confirmation tests using an actual vehicle were conducted to evaluate refrigerant leakage in a small garage. The verification conditions are summarized in Table 2 below.

Table 2 Garage gas leak test conditions

Leak amount [g]	Leak Rate [g/s]	Leak Location	Radiator e-Fan
150	13.5(Fast)	Center	OFF
150	13.5	Center	ON (max)
300	13.5	Center	OFF
300	13.5	Center	ON (max)
600	13.5	Center	OFF
600	13.5	Center	ON (max)
600	0.034(Slow)	Center	OFF
600	0.034	Center	OFF

The refrigerant leak amount was set between 150 and 600g. Two leak rates were evaluated: 13.5g/s to simulate a fast leak caused by a collision, and 0.034g/s to represent a slow leak, such as a pinhole in the heat exchanger. The leak location was positioned at the center of the underhood, area, above the e-Axle. Additionally, the effect of operating the on-board radiator e-Fan at maximum speed was assessed under each condition to evaluate its impact on reducing gas concentration.

The CFD verification setup is shown in Figure 4. Star CCM + was used to verify leakage inside a small garage.

【CFD condition】Star CCM+
Analysis method: Multicomponent gas CFD (Transient analysis)
Analysis period : 0～300 s
Initial: Air 100 %
Propane inflow: 13.51 or 0.034 g/s
e-fan speed : 0 or max Speed

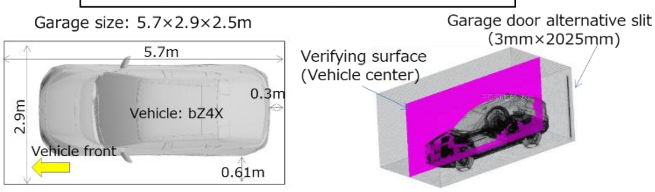


Fig. 4 CFD condition

The results for a 300g refrigerant leak are shown in Figure 5. Under conditions without fan operation, the gas released into the underhood area gradually settled near the floor. By 300 seconds, gas concentrations exceeding the LFL were observed near the floor. In contrast, when the e-Fan was activated immediately after the leak, airflow promoted the diffusion of stagnant gas, significantly reducing the high-concentration zone. After 300 seconds, the entire area was below the LFL.

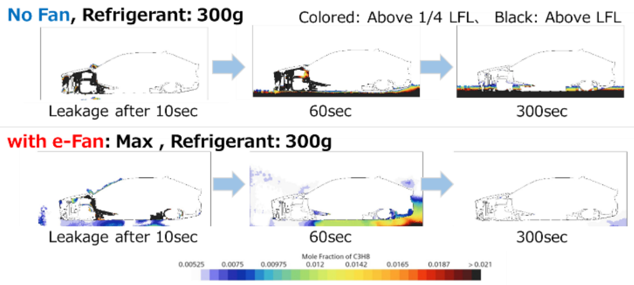


Fig. 5 CFD result (300g, with/without e-Fan)

To validate the CFD results, testing was conducted using an actual vehicle. The test vehicle was bZ4X, consistent with the CFD analysis. A small tent was set up in the laboratory showed in Figure 6 to simulate a small garage, including a 3mm-wide slit at the rear of the vehicle to represent a garage door opening. For safety reasons, equimolar, non-flammable CO_2 was used as a substitute for propane gas during the evaluation.

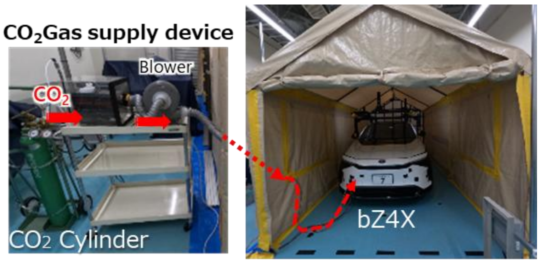
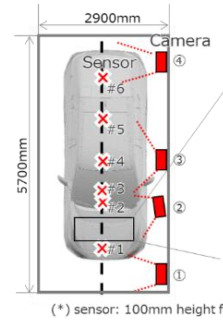


Fig. 6 Tent as garage and CO_2 gas supply device

As shown in Figure 7, the refrigerant leak amount, leak rate, and e-Fan operation, were evaluated under the same conditions as those used in the CFD analysis.

Item	Conditions
Leak location	Above the e-Axle
Test gas	CO2
Gas direction	Upper direction
Leak amount	150,300,600g
Leak rate	13.5、0.034g/s
e-Fan	OFF, ON(max speed)

◆Camera/Sensor location



◆Gas leaked position (Under-hood)

Fig. 7 Actual vehicle test condition

For gas measurement, an NDIR sensor was used, as shown in Figure 8. Its accuracy was ±0.2 pt near the LFL, where the verification was performed, and ±0.5 pt across the full measurement range, which was confirmed to be sufficient for the evaluation.

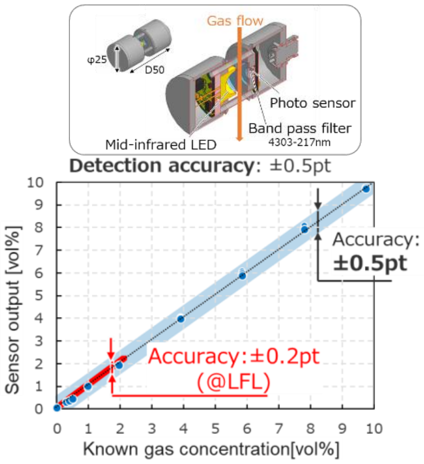


Fig. 8 NDIR concentration sensor

Figure 9 shows the results of an actual vehicle evaluation involving a fast leak of 600g of refrigerant, the most severe test condition. Without airflow, the gas concentration measured by the sensor placed 100mm above the floor exceeded the LFL 15 seconds after the leak began and remained above the threshold even after 300 seconds, indicating the accumulation of combustible gas. In contrast, when the e-Fan was operating, the concentration briefly exceeded the LFL at 30 seconds but was significantly reduced due to enhanced diffusion. By 300 seconds, the concentration had fallen below the LFL throughout the test area.

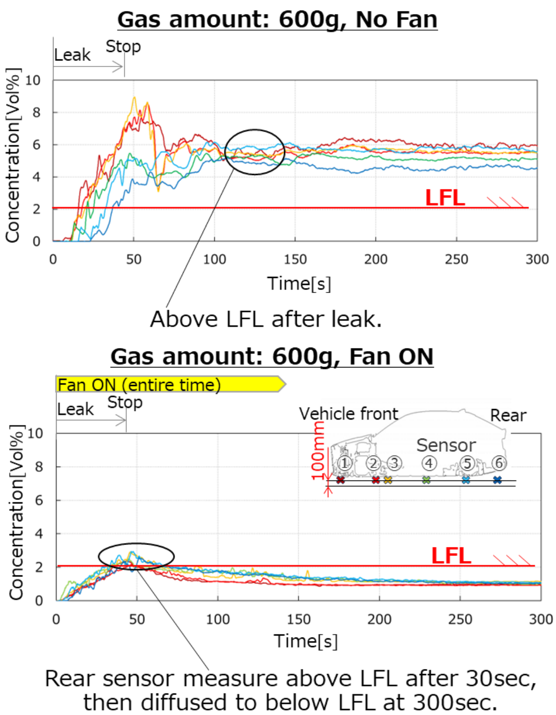


Fig. 9 Gas leakage in the garage (with/without e-Fan)

Figure 10 shows the maximum gas concentration at 300 seconds under varying leak amounts and rates. For fast leak conditions, concentrations exceeded the LFL at leak amounts above 150g. However, with the e-Fan operating, concentrations fell below the LFL for leak amounts up to 600g. Under slow leak conditions, the LFL was not exceeded even at 600g. Although the fast leak scenario represents an extremely conservative condition, the results clearly demonstrate the effectiveness of the e-Fan in promoting diffusion of leaked gas.

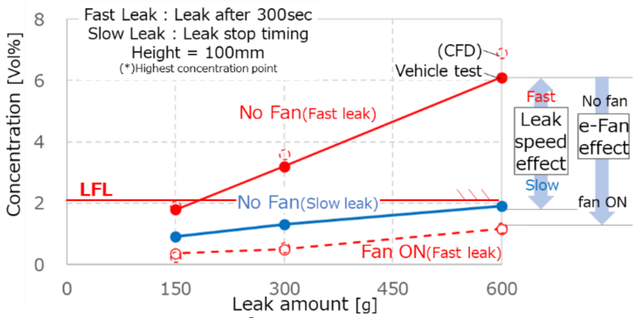


Fig. 10 Leak amount vs. concentration

GAS INTAKE INTO THE CABIN

Assuming the vehicle's air conditioning is operating, a vehicle evaluation was conducted to assess the potential for gas leakage from the underhood area to enter the passenger cabin through the HVAC outside air intake. As shown in Figure 11, CO_2 was used as the test gas. Sensors were placed near the driver's feet and face inside the cabin, and the HVAC blower speed was set to maximum during the evaluation.

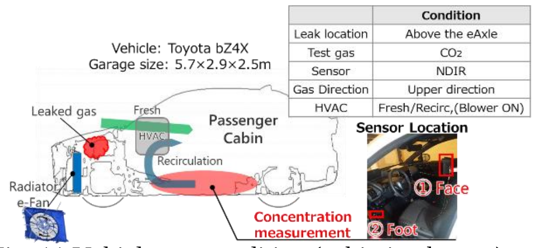


Fig. 11 Vehicle test condition (cabin intake test)

As shown in Table 3, the evaluation included the leakage amount, leakage rate, e-Fan operation, and impact of HVAC Fresh/Recirculation mode.

Table 3 Vehicle testing conditions

	Leak amount [g]	Leak Rate [g/s]	Leak Location	Radiator e-Fan	HVAC		
					Mode	Direction	Blower
1	150	13.5(Fast)	Center	Off	Fresh	Foot	High
2	150	13.5	Center	On(max)	Fresh	Foot	High
3	300	13.5	Center	Off	Fresh	Foot	High
4	300	13.5	Center	On(max)	Fresh	Foot	High
5	600	13.5	Center	Off	Fresh	Foot	High
6	600	13.5	Center	On(max)	Fresh	Foot	High
7	600	13.5	Center	Off	Recirc	Foot	High
8	600	13.5	Center	On(max)	Recirc	Foot	High
9	600	0.034(Slow)	Center	Off	Fresh	Foot	High
10	600	0.034	Center	On(max)	Fresh	Foot	High
11	600	0.034	Center	On(max)	Recirc	Foot	High

Figure 12 shows the concentration distribution near the driver's feet following a fast leak of 600g of refrigerant. In fresh air mode, with and without e-Fan operation, the concentration exceeded the LFL within 15 seconds due to gas intake through the HVAC system, then the concentration gradually decreased after 50 seconds. In contrast, in recirculation mode, a gas concentrations remained low throughout the evaluation.

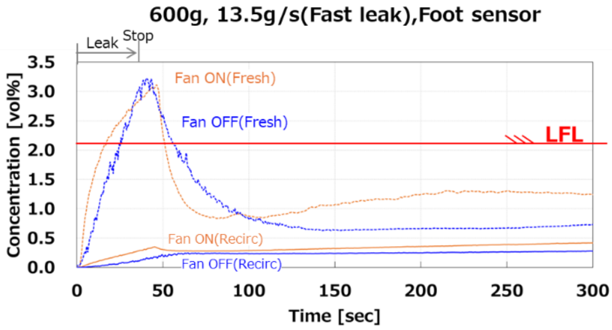


Fig.12 Comparison: fresh/recirc, fan ON/OFF (fast leak)

Figure 13 shows the cabin concentration result for a 600g leak with the e-Fan operating in fresh air mode. Under slow leak conditions, cabin concentration remained low and below the LFL up to a leak amount of 600g.

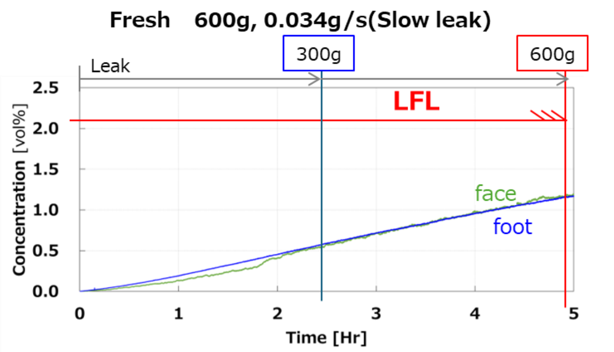


Fig. 13 Comparison: fresh (slow leak, fan ON)

Figure 14 shows the maximum gas concentration near the driver's feet under fast leak conditions, fresh air mode, and the HVAC blower operating at maximum speed. Under these conditions, the concentration exceeded the LFL when the leakage amount was 150g or more, regardless of the e-Fan operation. These results demonstrate that recirculation mode is effective.

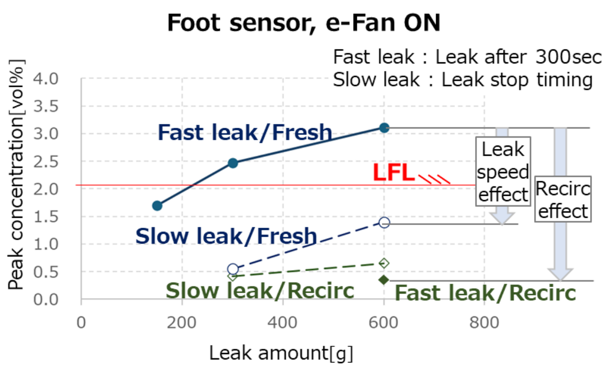


Fig. 14 Charge vs. concentration in the cabin

LEAK INTO THE COOLING LOOP

The thermal management system for R290 refrigerant requires a secondary loop for heating and cooling the cabin to prevent direct gas leakage into the cabin. In the secondary loop, a heat exchanger -such as a water-cooled condenser- is installed between the refrigeration cycle and the cooling loop. The third leakage scenario examines the impact of refrigerant leakage into the cooling loop due to damage to this heat exchanger. As shown in Figure 15, the study considers two conditions: (1) gaseous refrigerant intrusion, which is the most likely scenario, and (2) liquid refrigerant intrusion, representing the most severe case.

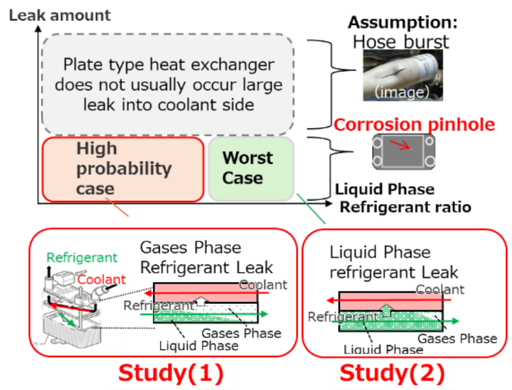


Fig. 15 Gas /Liquid leakage into the cooling loop

The cooling loop, configured as a heating loop for a BEV, is shown in Figure 16. It includes a water-cooled condenser, an electric water pump, a heater core, a reserve tank with a relief valve, and a visualization sight glass. To monitor valve operation, a visualization window was machined into the relief valve, allowing direct observation of its status during the test.

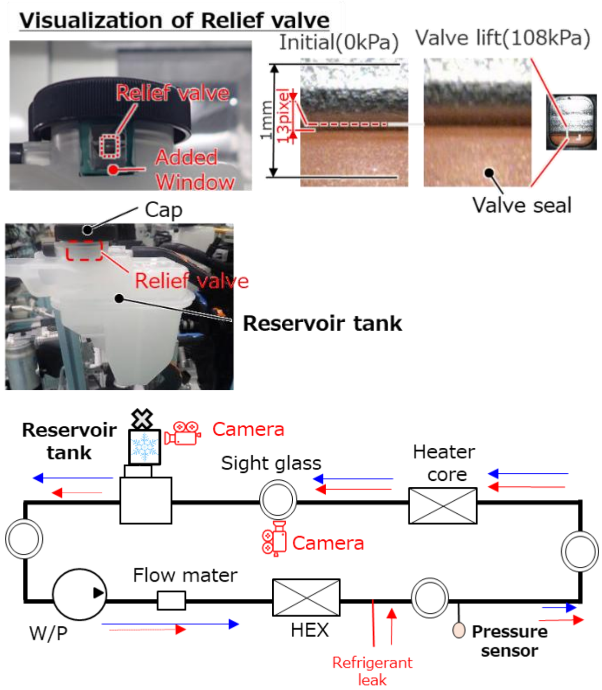


Fig. 16 Verified cooling loop and visualization point

The test conditions were an initial temperature ranging from -30 to 40°C, a concentration of 50% automotive ethylene glycol in the coolant water flowing at 5 L/min, and refrigerant gas introduced into the coolant loop at 30g/h.

Table 4 Test conditions

		Conditions
Environment / Coolant	Initial temperature	-30, -20, -10, 0, 20, 40 ℃
Coolant	Concentration ratio	Ethylene Glycol/Water 50%
	Flow rate	5L/min
Refrigerant	Leak rate	30g/h, (Gas Phase)

The evaluation results are shown in Figure 17. Although the refrigerant intrusion caused a pressure increase of approximately 10 kPa, the pressure rise was controlled by the operation of the relief valve. No rupture or bursting of the cooling loop hoses occurred under any temperature condition.

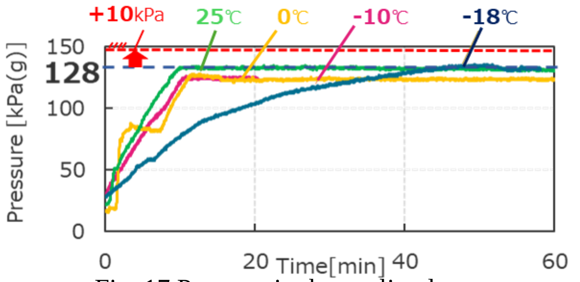


Fig. 17 Pressure in the cooling loop

Figure 18 summarizes the initial temperature and valve operating state based on the relief valve visualization results. The valve functioned normally even at low temperatures, and anticipated sticking due to freezing did not occur.

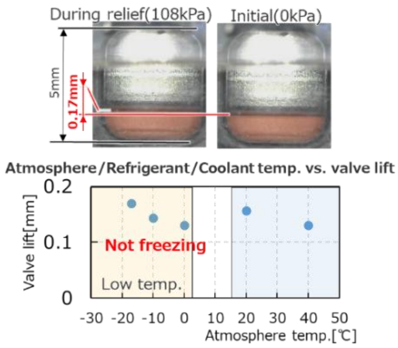


Fig.18 Temperature vs. relief valve lift

Next, we evaluated the potential for liquid refrigerant intrusion under worst-case conditions. As shown in Figure 19, if low-temperature liquid refrigerant enters the cooling loop, there is a concern that the coolant may freeze due to the latent heat of refrigerant vaporization, which occurs following a pressure drop after intrusion. To assess this risk under particularly severe conditions, we examined the possibility of freezing during a steady-state condition. Additionally, since liquid refrigerant leakage from the heat exchanger is assumed to be transient during warm-up, we investigated whether freezing could occur during this phase using temperature and visualization techniques.

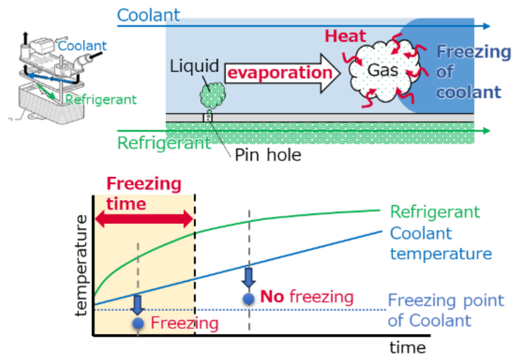


Fig. 19 Freezing mechanism in the cooling loop

Figure 20 shows the test equipment used in this evaluation. We developed a device that directly injects refrigerant, preconditioned to a specific temperature, into the cooling loop through a prototype injector designed to replicate a crack in the heat exchanger.

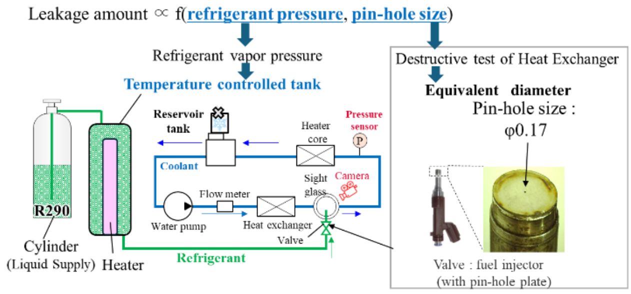


Fig. 20 Test rig set up of liquid propane injection

To simulate worst-case conditions, we conducted evaluations under two steady-state scenarios: a coolant concentration of 30% at temperatures of -15°C (Freezing condition shown in table 5) and -10°C (no Freezing condition).

Table 5 Coolant concentration vs. freezing temperature

Coolant concentration [%] (automotive ethylene glycol)	30%	35%	40%	45%	50%
Freezing temperature [maximum ℃]	-15	-20	-25	-30	-35

As shown in Figure 21, under steady-state conditions with a coolant temperature of -15°C, it took about 10 minutes from the intrusion of liquid refrigerant to the start of freezing, after which a pressure increase was observed. For comparison, since freezing was not observed at a coolant temperature of -10°C, we checked whether a temperature rise of $\Delta T = +5$°C within 10 minutes occurred under warm-up transient conditions.

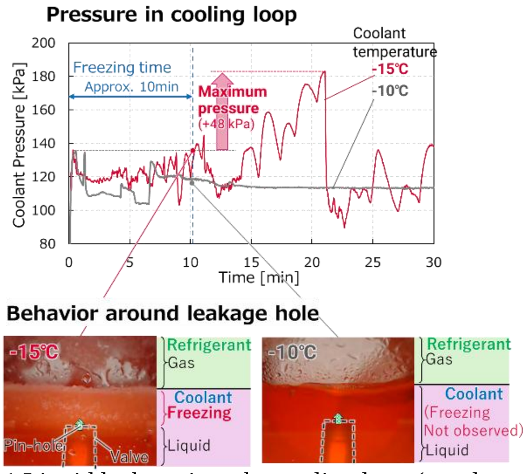


Fig. 21 Liquid leakage into the cooling loop (steady state)

Assuming an actual warm-up situation, the evaluation was carried out under conditions where the initial water temperature was -15°C, which is the temperature at which freezing occurred in a steady state. As shown in Figure 22, the temperature rose to ΔT = +5°C within 2.5 minutes after the start of warm-up, which was earlier than the 10 minutes as criteria to start of freezing. It was found that in an actual warm-up transient state, the risk of relief valve sticking, abnormal pressure, and circuit damage due to freezing was low.

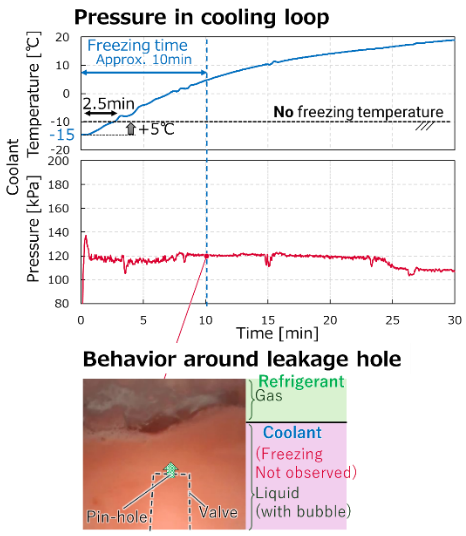


Fig. 22 Liquid leakage into the cooling loop (warm up)

CONCLUSIONS

Assuming a thermal management system using R290 refrigerant, evaluations were conducted under three scenarios: (1) Garage, (2) Passenger cabin, and (3) Cooling loop refrigerant leakage. The following conclusions were obtained:

(1) Garage Gas Leakage Scenario
- With refrigerant leakage of 600g or less and the e-Fan operating, the gas concentration can be reduced to below LFL even under the worst-case conditions of a fast leakage rate.
- Under slow leakage conditions, leakage of 600g or less not exceeded the LFL

(2) Passenger Cabin Gas Intrusion Scenario
- Recirculating HVAC air within the vehicle can prevent leaked refrigerant from entering the passenger cabin.

(3) Cooling Loop Refrigerant Intrusion Scenario
- Freezing of the cooling loop and relief valve due to gas refrigerant intrusion does not occur even in low temperature environments.
- Although gas refrigerant intrusion causes a pressure increase, the relief valve operates effectively to prevent cooling loop rupture or explosion.
- When liquid refrigerant enters the cooling loop under steady-state conditions at -15°C, freezing occurs; however, the relief valve does not stick, and no extreme pressure rise or circuit damage is observed.
- During warm-up transient conditions, liquid refrigerant intrusion initially causes freezing, but as water temperature rises, the freezing is resolved quickly. No relief valve sticking, or circuit damage occurs.

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将来 xEV における R290 冷媒使用の安全性向上に関する研究
Research on enhancing safety of using R290 refrigerant in future xEVs

林 邦彦・宮里 佳明　トヨタ自動車 (株)
清水 智紀　(株) SOKEN

Kunihiko Hayashi*, Yoshiaki Miyazato*, Tomoki Shimizu**
*Toyota Motor Corporation, 1200 Mishuku, Susono, Shizuoka, 410-1193, Japan
**SOKEN inc., 500-20 Minamiyama, Komenoki-cho, Nisshin, Aichi, 470-0111, Japan

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Key Word: Refrigerant leakage, R290 , Propane , Natural Refrigerant

1．はじめに

地球温暖化や環境問題を発端に各国でカーボンニュートラル活動や電燃費・CO_2 規制が進み、自動車業界では電動車における電燃費・航続距離向上の取り組みが急務である。特に電気自動車では冬の暖房電費向上のためヒートポンプ搭載が進んでおり、更なる効率向上のためヒートポンプに適した新冷媒の検討が進められている[1]一方、欧州における PFAS 規制化も想定し、様々な冷媒を候補に開発を進める必要がある。

PFAS に該当せず、冷暖房性能・効率が良い自然冷媒の R290（プロパン）は、家電や業務用での認可、規格化や安全検討が進む一方、表 1 に示すように、現在自動車用途では使用許可が下りておらず、規格も未策定である[2][3][4]。

Table 1 Natural refrigerant candidates

	Refrigerant	EU PFAS definition	Performance Heating	Performance Cooling	Standard (for Auto)	Flammability
Current	R1234yf	× (Subject to PFAS)	○	○	○	A2L
Natural Refrigerant	CO2 (R744)	✓(non PFAS)	○+	○−	○	−
	Propane (R290)	✓(non PFAS)	○+	○+	N/A	A3

本研究では可燃性 R290 冷媒について、将来の規格化を想定し、実車と CFD を用いた安全性検証を行う。

自動車用 R290 冷媒の規格化については、昨年米国で当局に使用申請(SNAP)が行われたことを発端に、SAE（米国自動車技術会）内で議論が進んでいる。弊社としては、本研究を通し、これら規格化の貢献に加え、ISO26262 に代表される、フェールセーフを備えた安全なシステム設計を進めていく。本研究は図 1 に示すリスク要素のうち可燃混合気に着目し冷媒漏洩時の安全検証を行う。

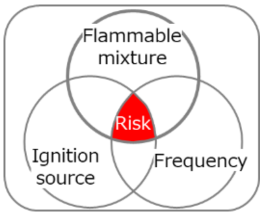

Fig.1 Risk factor

2．検討シナリオ

フロントコンパートメントに冷凍サイクルを搭載する車両は、冷媒ガスの漏洩ルートとして、図 2 のように、①外部への直接漏洩、②客室へのガス侵入、③冷却回路を通じた外部又は客室への漏洩が想定される。SAE ではリスクアセス検討結果、厳しい条件として、小型ガレージ内時の漏洩を指摘しており、本検討はこの条件で検証を行った。

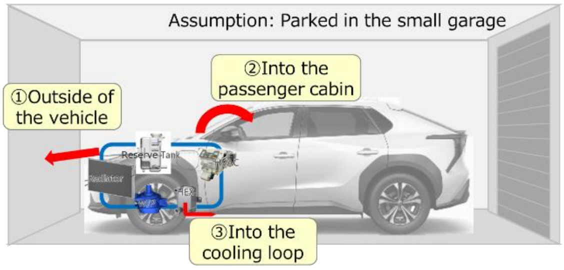

Fig.2 Possible Gas leak route

３．ガレージにおける車外漏洩検証

CFD と実車を用い、図 3 に示す小型ガレージ内での車両外部ガス漏洩を検証する。また漏洩時リスク削減策として、車載ラジエータファン作動による強制対流を用いた濃度低減効果も検証する。車両は BEV のトヨタ bZ4X とし、ガレージ後方にガレージシャッターを想定した 3mm 幅スリットを縦方向に設定し、外部との換気を再現している。

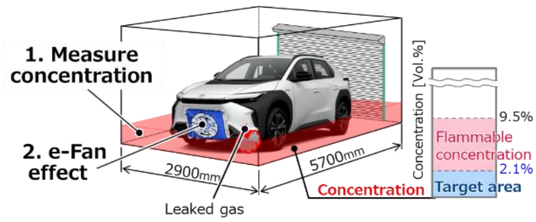

Fig.3 Environmental condition

R290 は可燃下限濃度(LFL)が 2.1vol%であり、この値を安全性の閾値として検証を進める。小型ガレージ内における冷媒漏洩評価については、CFD による評価に加え、実車を用いた確認試験も行う。検証条件を以下表 2 に示す。

Table 2 Garage gas leak test conditions

Leak amount[g]	Leak Rate [g/s]	Leak Location	Radiator e-Fan
150	13.5(Fast)	Center	OFF
150	13.5	Center	ON (max)
300	13.5	Center	OFF
300	13.5	Center	ON (max)
600	13.5	Center	OFF
600	13.5	Center	ON (max)
600	0.034(Slow)	Center	OFF
600	0.034	Center	OFF

冷媒充填量は 150～600g、漏洩速度は衝突事故相当の速い漏れとして 13.5g/s、熱交換器のピンホール穴漏れ相当の遅い漏れとして、0.034g/s を設定し、漏洩位置はフロントコンパートメント内中央部、e-Axle 上方放出としている。また、各条件において、車載ラジエータファンを最大速度で作動させた効果も検証した。図 4 に示すように、CFD 解析は Star CCM+を活用し、検証を行った。

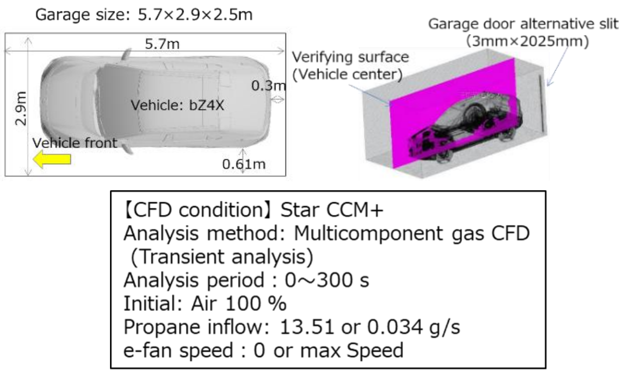

Fig.4 CFD condition

冷媒漏洩量 300g の結果を図 5 に示す。無風条件では、漏洩直後フロントコンパートメント内に放出したガスが次第に床付近に沈降し、300 秒時点で床付近に LFL を越える濃度のガスが存在する。一方、漏洩直後に車載ファン稼働する条件では、風流れで滞留ガス拡散が促進され高濃度範囲が大幅に減少、300 秒後に全域で LFL を下回った。

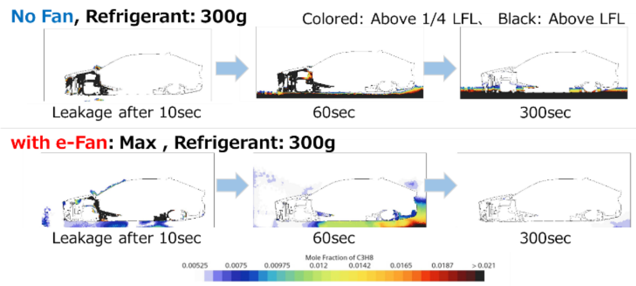

Fig.5 CFD result (300g, with/without e-Fan)

CFD 結果実証のため、実車を用いた検証を行った。車両は CFD 同様 bZ4X を用い、小型ガレージは、図 6 に示すように、実験室内に小型テントを設置し、車両後方のシャッターを想定した 3mm 幅スリットも再現している。検証では安全性を考慮し、プロパンガス代替として等モル質量で不燃性の CO_2 を代替ガスとして評価に用いた。

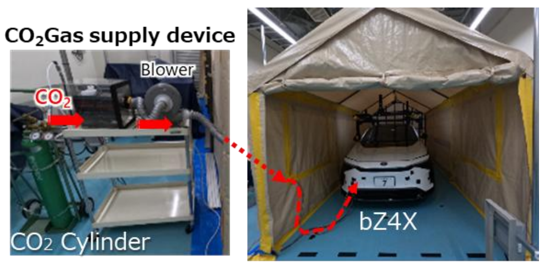

Fig.6 Tent as garage and CO_2 gas supply device

図 7 に示すように、フロントコンパートメント内、e-Axle 上方にガスを放出する条件で実証試験を行った。ガス漏洩量、速度、車載ファン作動条件についても CFD と同条件で評価を行っている。

Item	Conditions
Leak location	Above the e-Axle
Test gas	CO_2
Gas direction	Upper direction
Leak amount	150,300,600g
Leak rate	13.5、0.034g/s
e-Fan	OFF, ON(max speed)

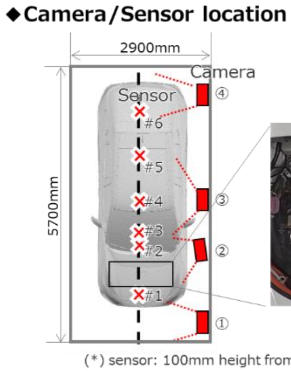

Fig.7 Actual vehicle test condition

ガス計測には、図 8 に示す NDIR センサーを活用した。検証を行う LFL 付近で±0.2pt、全域で±0.5pt の精度であり、検証に十分な能力であることを確認した。

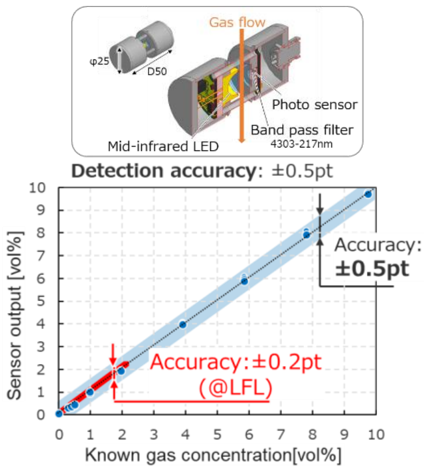

Fig.8 NDIR concentration sensor

実車評価結果として、最も厳しい条件となる、速い速度で 600g 漏洩した結果を図 9 に示す。無風条件では、床から高さ 100mm に設置したセンサー濃度が、漏洩 15 秒以降で LFL を越え、300 秒経過後も高い状態を維持し、可燃ガスが滞留することが分かる。一方で、漏洩直後から車載ファンを稼働させると、30 秒以降で一時的に LFL を越えるものの、拡散が促進され濃度が減少、300 秒時点では LFL を下回る結果となった。

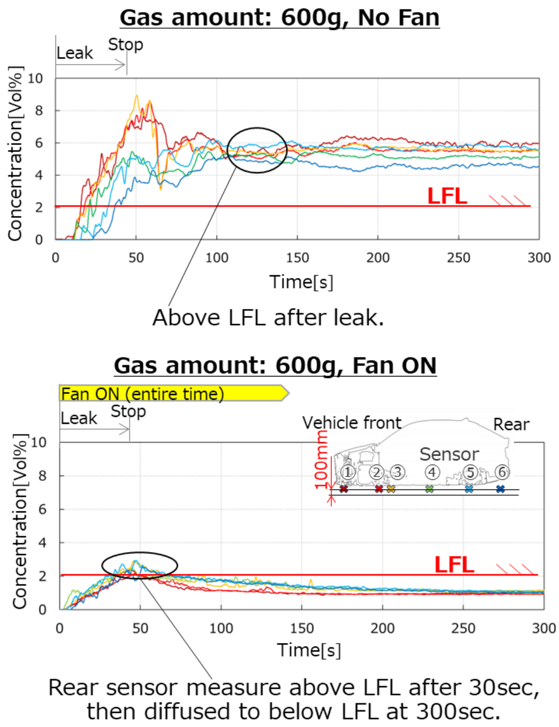

Fig.9 Gas leakage in the garage (with/without e-Fan)

漏洩量と速度を変化させた際の、300 秒時点の最高濃度をまとめた結果を図 10 に示す。速い速度の漏洩では、150g を越える漏洩量で LFL を超過する一方、車載ファン作動により、漏洩量 600g 以下で LFL を下回る結果となった。また遅い漏洩速度では漏洩量 600g まで LFL を超過しない。今回極端に厳しい条件として速い漏れ速度の評価を行ったが、車載ファンによる漏洩ガス拡散効果が実証された。

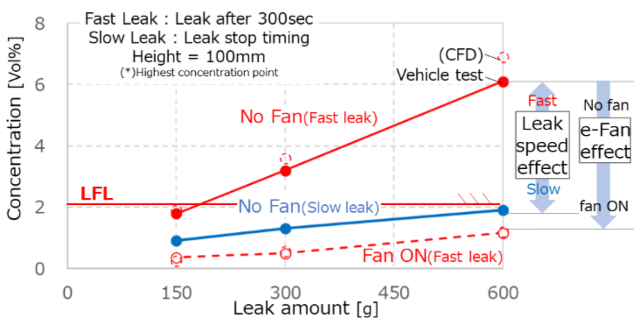

Fig.10 Leak amount vs. concentration (vehicle test)

4．車室内へのガス侵入検証

車内でのエアコン作動を想定し、フロントコンパートメントで漏洩したガスが、HVAC の外気取り入れ口より車室内へ侵入する可能性について、実車評価を行った。図 11 に示すように、評価ガスとして CO_2 を活用し、車室内の運転席足元と顔付近にセンサーを設置、HVAC ブロワー速度を最大として評価を行った。

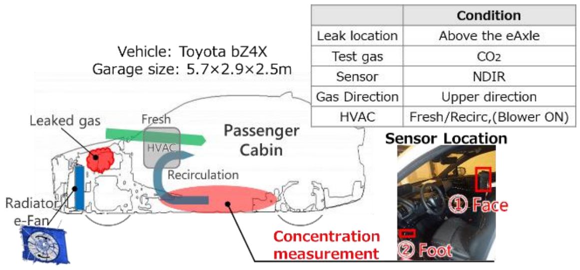

Fig.11 Vehicle test condition (cabin intake test)

評価は表 3 のように、漏洩量、漏洩速度、車載ファンの作動有無に加え、HVAC 外気導入/内気循環による影響を評価した。

Table 3 Vehicle testing conditions

	Leak amount [g]	Leak Rate [g/s]	Leak Location	Radiator e-Fan	HVAC Mode	HVAC Direction	HVAC Blower
1	150	13.5(Fast)	Center	Off	Fresh	Foot	High
2	150	13.5	Center	On(max)	Fresh	Foot	High
3	300	13.5	Center	Off	Fresh	Foot	High
4	300	13.5	Center	On(max)	Fresh	Foot	High
5	600	13.5	Center	Off	Fresh	Foot	High
6	600	13.5	Center	On(max)	Fresh	Foot	High
7	600	13.5	Center	Off	Recirc	Foot	High
8	600	13.5	Center	On(max)	Recirc	Foot	High
9	600	0.034(Slow)	Center	Off	Fresh	Foot	High
10	600	0.034	Center	On(max)	Fresh	Foot	High
11	600	0.034	Center	On(max)	Recirc	Foot	High

漏洩量 600g、速い漏洩における運転席足元付近の濃度分布を図 12 に示す。車載ファン作動の有無に関わらず、外気導入時はガス侵入により漏洩 15 秒以降 に LFL を越え、その後濃度は低下する。一方、内気循環とすることで、車室内は低濃度が維持される。

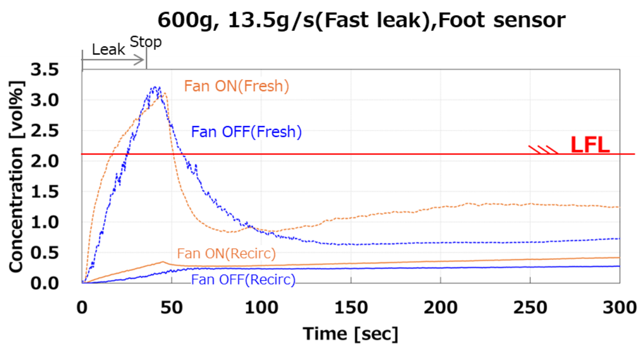

Fig.12 Comparison: fresh/recirc, fan ON/OFF (fast leak)

図 13 に漏洩量 600g、遅い漏れで車載ファン作動、外気導入条件での車室内濃度を示す。遅い漏れでは濃度は低く、600g 相当の漏洩でも、LFL 以下の濃度となった。

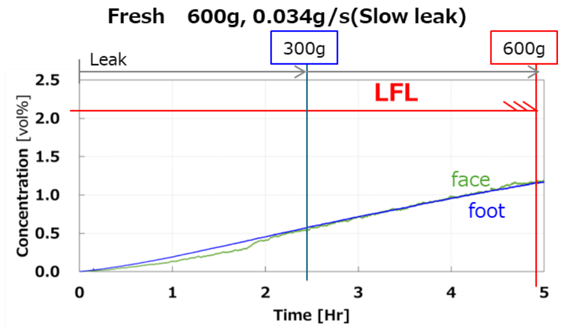

Fig.13 Comparison: fresh (slow leak, fan ON)

漏洩量に対する運転席足元付近の最大濃度を図 14 に示す。車載ファン作動時に速い漏洩で外気導入、ブロワー速度最大稼働すると、漏洩量 150g 以上で濃度が LFL を越える。内外気切り替えの濃度変化影響大きく、車室内への侵入防止には、内気循環が効果的であることが実証された。

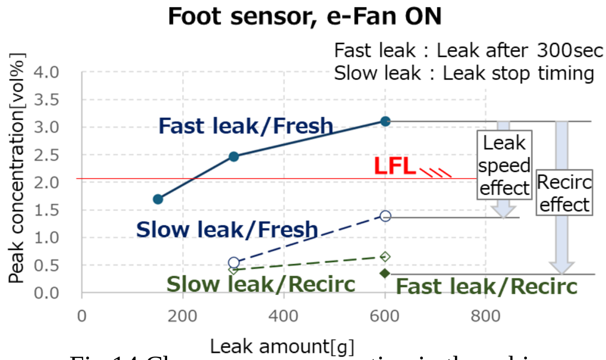

Fig.14 Charge vs. concentration in the cabin

５．冷却回路への漏洩検証

R290 冷媒用車載温調システムは、車内直接ガス漏洩防止のため、冷却回路を介して車室内冷暖房熱供給を行う 2 次ループ構成が求められる。2 次ループでは、冷凍サイクルと冷却回路間に水冷式コンデンサ等熱交換器を設置する。3 つめの漏洩シナリオでは、この熱交換器損傷による冷却回路への冷媒漏洩影響を検証する。図 15 のように、本検討では熱交換器の冷媒漏れ条件として可能性が高い(1)気体冷媒侵入に加え、凍結リスク高い最悪条件として(2)液冷媒の侵入評価も行った。

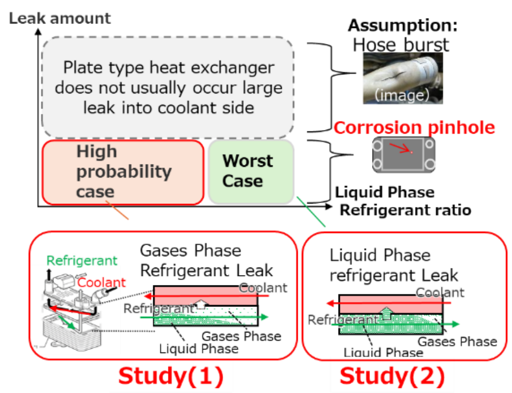

Fig.15 Gas/Liquid leakage into the cooling loop

冷却回路は図 16 のように、BEV 用暖房回路を想定した回路とした。回路には、水冷コンデンサ、電動ウォーターポンプ、ヒーターコアと、リリーフバルブを備えたリザーブタンクに加え、可視化用サイトグラスを備える。リリーフバルブには弁作動状態確認のため、可視化窓加工を行った。

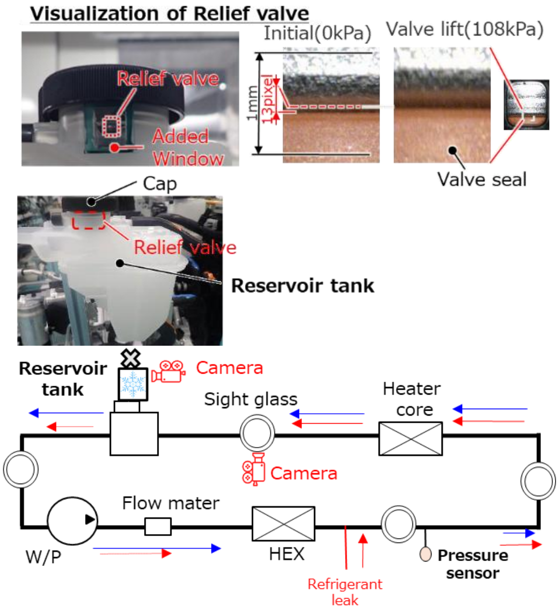

Fig.16 Verified cooling loop and visualization point

試験は表 4 に示す異なる初期温度にて、自動車用エチレングリコール濃度 50%冷却水を用い、冷却水流量 5L/min の条件下で冷媒ガスを投入した。

Table 4 Test conditions

		Conditions
Environment / Coolant	Initial temperature	-30, -20, -10, 0, 20, 40 ℃
Coolant	Concentration ratio	Ethylene Glycol/Water 50%
	Flow rate	5L/min
Refrigerant	Leak rate	30g/h, (Gas Phase)

評価結果を図 17 に示す。冷媒侵入により 10kPa 程度圧力上昇生じるものの、リリーフバルブ作動により圧力上昇抑制され、各温度条件において、冷却回路ホース破断や破裂は生じない。

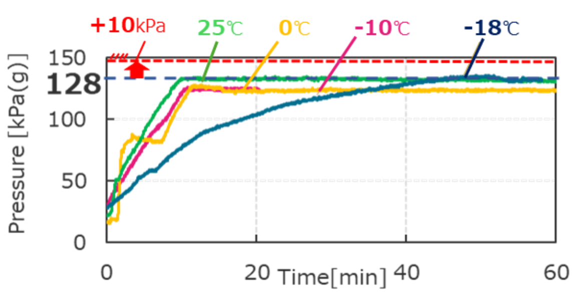

Fig.17 Pressure in the cooling loop

リリーフバルブ可視化結果から、初期温度と弁の作動状態を図 18 にまとめる。低温域においても弁は正常に作動し、懸念される凍結による固着は生じなかった。

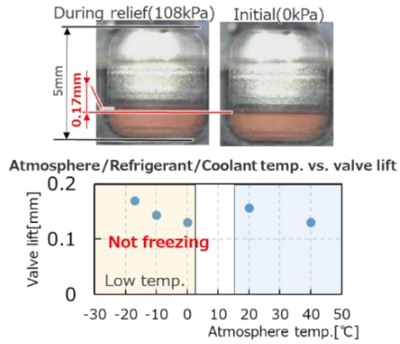

Fig.18 Temperature vs. relief valve lift

次に、最悪条件を想定した液冷媒侵入評価を行う。図 19 のように低温で液状態の冷媒が冷却回路に進入した場合、侵入後の圧力低下起因の冷媒気化潜熱により冷却水凍結が懸念される。最悪条件想定し、まず水温一定で凍結可能性を確認した。一方、熱交換器からの液冷媒漏洩は暖機過渡と想定されるため、水温上昇する過渡条件で凍結が生じるか、温度と可視化による検証を行った。

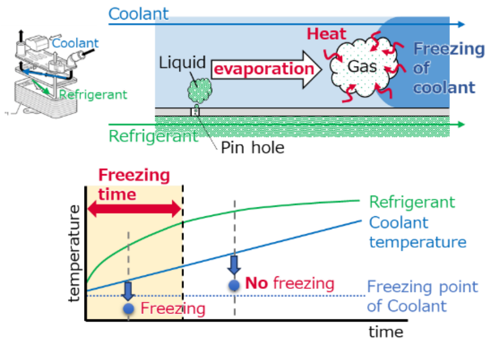

Fig.19 Freezing mechanism in the cooling loop

試験装置を図 20 に示す。所定の温度に調整した冷媒が、熱交換器のクラック穴面積を噴射口として試作再現した試作インジェクタを介して冷却回路に直接投入する装置を製作した。

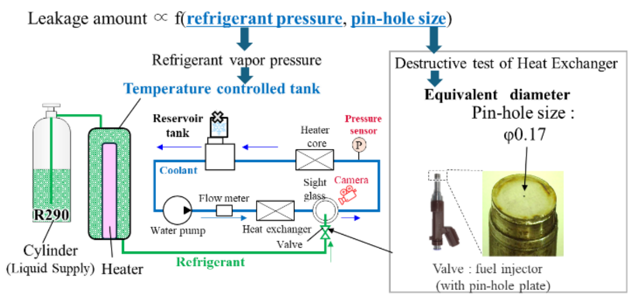

Fig.20 Test rig set up of liquid propane injection

始めに凍結状況確認のため、表 5 に示す冷却水濃度 30%、-15℃定常条件にて評価を行った。

Table 5 Coolant concentration vs. freezing temperature

Coolant concentration [%] (automotive ethylene glycol)	30%	35%	40%	45%	50%
Freezing temperature [maximum ℃]	-15	-20	-25	-30	-35

図 21 に示すように、水温-15℃定常条件では、液冷媒侵入から凍結開始までに約 10 分かかり、それ以降で圧力の上昇がみられた。なお、比較として水温-10℃では凍結が生じないことから、10 分以内に ΔT=+5℃の昇温が暖機過渡条件で生じるか確認を行った。

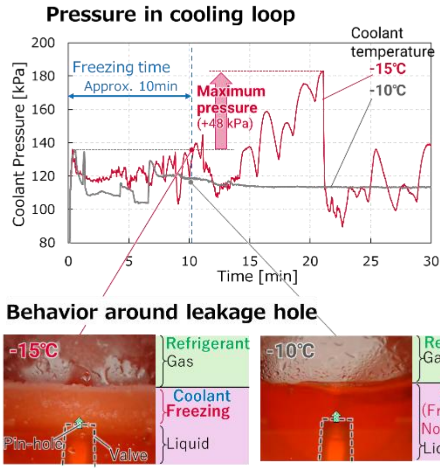

Fig. 21 Liquid leakage into the cooling loop (steady state)

一般的な使用状況を想定し、定常条件で凍結が発生した初期水温-15℃にて、暖機過渡条件の評価を行った。図 22 に示すように、暖機開始後 2 分半以内に ΔT=+5℃の温度上昇に達し、凍結開始の基準とした 10 分よりも早く、圧力の異常な上昇も見られなかった。実際の暖機過渡状態においては、凍結によるリリーフバルブ固着、冷却回路の異常圧力や損傷のリスクが低いことが分かった。

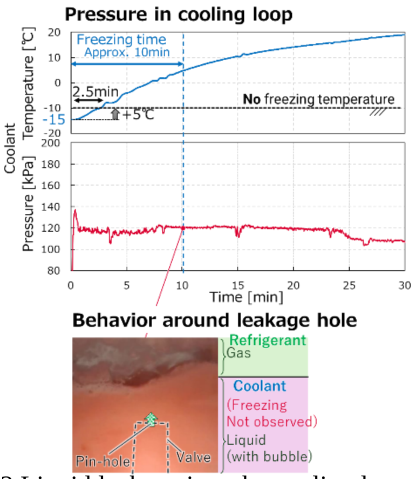

Fig. 22 Liquid leakage into the cooling loop (warm up)

６． 結論

R290 冷媒用車載温調システムを想定し、(1) ガレージ、(2) 車室、(3) 冷却回路冷媒漏洩シナリオにおける評価を行い、以下の結論を得た。

(1) ガレージシナリオ
- 冷媒漏洩 600g 以下、かつ車載ファン作動により、最悪条件の速い漏洩速度でも LFL 以下に濃度を下げることができる。
- 遅い漏れ条件においては漏洩 600g 以下で LFL を越えることは無い

(2) 車室侵入シナリオ
- HVAC 内気循環とすることで漏洩冷媒の車室内侵入を抑止できる

(3) 冷却回路侵入シナリオ
- ガス冷媒侵入による回路内及びリリーフバルブの凍結は低温環境でも生じない
- ガス冷媒侵入で圧力上昇あるものの、リリーフバルブ作動により、回路の破断や破裂を防止することができる
- 液冷媒侵入により、-15℃定常条件で冷却水凍結が生じるが、リリーフバルブは固着せず、極端な圧力上昇や回路の破損は生じない
- 暖機過渡条件での液冷媒侵入では、水温上昇が早いため、凍結は短時間で解消され、固着や回路破損は生じない

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