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CONTROLLING OF TRAIN'S INTERIOR HEATING SYSTEM FOR MAXIMUM ENERGY EFFICIENCY

Summary. Heating systems in diesel multiple unit (DMU) trains often use additional mechanical and/or electrical auxiliary power, increasing fuel consumption, while waste heat is available from the diesel engine. Delivery of waste heat for heating of multiple carriages is analysed as realized in DR1 and D1 series trains, in light of the current standards of passenger comfort and in-depth testing of DR1B trains. A new hybrid hot air and electrical heating system and its control algorithm is reviewed for modernized DR1AC trains of Latvian railways, capable of extracting waste heat from three different sources and supplemented by two additional sources in case of shortage, for full conformance to EN 14750-1 standard. Results of factory testing are included.

1. INTRODUCTION

Environmental conditions in the train interior are one of the key criteria for the passengers. In certain cases, unsuccessful design and/or operation of heating system can even be the main reason to judge against travelling by rail during the cold season. For these reasons, stable and comfortable conditions for the passengers must be provided in the train interior, not dependent on the train occupancy level, outside air temperature or train operational mode, to safeguard attractiveness of the railway transport in the eyes of the passengers.

Problems with heating systems mostly affect and influence train operators, but the core reason for these problems mostly lies in the design of the train; thus, the train operator is unable to rectify design faults, and the solutions must be developed and tested thoroughly during design and certification stages. As indicated in Berlitz and Matschke [4], economical boundary conditions have forced the manufacturers to reduce cost and “time-to-market”, which means less time for testing and optimization. Although standard for heating systems (EN 14750, [18-19]) set quite high level of requirements for the heating systems, the testing conditions not always respect the actual train operational conditions, this being the case especially for diesel multiple unit trains (DMU trains). Thus, heating power under certain conditions can be limited and insufficient for maintaining stable interior conditions.

At the same time, it must be remembered that DMU trains are internal combustion trains, and any power used for auxiliaries like heating increases fuel consumption, except in one case – if engine waste heat is used. Thus, any heating system that avoids additional loading on the diesel engine and uses engine waste heat will be more energy efficient than heating systems depending on auxiliary mechanical power. This is the topic for this article, as usage of engine waste heat for passenger interior heating, especially for multiple carriage, requires specific designs and increases energy efficiency, but with few drawbacks, including more complicated design and testing.

During the design of deeply modernized DMU trains for Latvian railways (series DR1AC, modernized 2014-2016), a hybrid heating system was developed to utilize heat from engine jacket cooling liquid (main diesel engine and auxiliary diesel-generator), indirectly also from hydrodynamic transmission oil and additional Webasto diesel fuel heater for supplementation purposes in case if engine load conditions are low. Heat from cooling liquid is transferred by water-to-air heat exchangers to fresh outside air to be delivered to all three train carriages (four separate passenger compartments), and utilizing electric blowers installed in the passenger compartments for balancing and additional heat supplementation purposes.

The author proposes that the best solution has been found for controlling of this hybrid heating system, for simultaneous achievement of full compliance on heating requirements as per standards of interior heating [18], while achieving maximum energy efficiency, using engine waste heat as much as possible and ensuring passenger comfort.

2. LITERATURE REVIEW

Rising energy costs and possible diesel fuel scarcity drive innovations and research towards seeking of new solutions [11]; this is true not only to new designs but to retrofits and modernizations as well [6].

Waste heat recovery has been used for decades in automotive industry, off road and agricultural machinery, small airplanes (exhaust shroud heaters), and as well in railway rolling stock – for heating of driver cabs in locomotives, for heating of passenger compartment in single-car diesel trains (railcars), and for the heating of driver and personnel cabins on track repair machinery. Implementation of waste heat recovery for heating of multiple unit trains has been realized in the DR1 and D1 series DMU trains [28] in regular service for more than forty years, although without full compliance to modern requirements, and only DR1 series trains have a hybrid heating system (hot air and electrical).

As the standards regulating passenger train heating, ventilation and air conditioning [18-19] only state achievable parameters, but do not present a standardized calculation methodology, rolling stock designers are relying on common guidebooks and their previous experience in the field to achieve a satisfactory design. As correctly stressed also by Berlitz and Matschke [4], design evaluation and optimization must be done at the design level, as modelling on full scale is very costly and time consuming, and at the stage of train “as-built”, only fine tuning is possible, and if the system is seriously underperforming, the only possibility is to rework the design and remanufacture from scratch, thus implying huge risks and associated costs. In this view, waste heat recovery and usage become an especially complicated topic, taking into account the unpredictable engine load conditions and high level of power necessary for heating of multiple carriage trainset, as analyzed in more details below.

Performance of heating system design has been improved recently with revised theories and modelling tools, with research devoted mostly on two topics – macroscopic level studies of heat energy balance, especially under transient conditions (see [5, 13, 25]), investigation of thermal inertia of the air in the passenger compartment [26], and microscopic level studies of air velocities, temperature gradients by utilizing computerized fluid dynamic (CFD) simulations, with the latter acquiring more and more attention.

It must be noted that it is a “tradition” of railway transportation heating calculations to model a single object/unit; in the older works, this always reflected an entire passenger carriage. Nowadays, with popularity of multiple unit trains and articulated consists, the object of modelling is either a separate carriage or an entire train interior in case of an articulated train. These traditions of modelling are transferred also to other rail-bound transport means - trams [20] and light rail [21]. It is interesting to note that even locomotive hauled closed-space passenger coaches, which have several compartments separated by wooden internal walls, are not treated as separate compartments but as one large compartment, introducing in the energy balance additional members reflecting the thermal inertia of the walls [5]. This is contrary for the example to automotive industry, where in the interior of

a passenger car, four different climatic zones are realized and calculation models accordingly reflect that, even without partition walls [17].

Many aspects of the heating systems and the problems to be solved are similar with air conditioning systems, thus calculation models like Емельянов et al [25] share similarity, usually with the opposite heat flow direction and peculiarities regarding air recirculation. Moreover, more interest in development of air conditioning systems can be seen than in the development of energy-efficient heating systems, as indicated for example by patent review [15] and by review Емельянов et al [27]. Some notable ideas for passenger carriage heating from new sources are discussed in Габринец et al [24], for example, recovery of heat from exhausted ventilation air, whereas others – capture of sun radiation due to “greenhouse” effect of optimized window glass – cause serious doubts, taking into account the whole year-round operational needs.

An interesting article [23] is devoted to the idea of heat recovery during braking of the train by hydrodynamic brakes attached to wheels. Although the idea has potential, the solution proposed is too complex and has serious disadvantages. The author wishes to note that the same idea can be easily realized in DR1 series trains, as the cooling of the hydrodynamic transmission is done by the same cooling liquid as the main diesel engine. The same principle is already used for preheating of the train passenger compartments, by utilizing the “stop-regime” in DR1B and DR1AC trains (stated later).

Regarding the microscopic level studies, owing to only the last decade advances in computing power and the historically deep-rooted reluctance of railway industry to innovations, these topics are historically less covered in articles; one of the first reports of railway application found by author date to year 2001 (reported in journal in 2006) [4], and a study of a TGV high-speed train for ventilation optimization was published in 2014 [2]. Article [10] published in 2007 is devoted to the challenges of CFD calculation of the transient processes during opening and closing of doors with evaluation of part of the train. However, the first articles devoted to railway interior studies with properly modelled manikins with metabolism can be found in Konstantinov and Wagner [16] published in 2015, commenced by Aliahmadipour et al [1] and Suárez et al [20] in 2017. This is contrary to a wider and earlier application of CFD studies in other industries, for example, in aviation, see article [14] published in 2006, or in automotive industry, see an article [12] published 2005. Article [3] from automotive industry proves by comparison CFD modelling with and without manikins that presence of manikins in the interior has influence on the air flow patterns and thermal comfort levels. Lately CFD studies of ventilation systems have been used for very specific purposes, for example, investigation of cough droplet dispersion and removal in China high-speed train interior [22].

The topic of waste heat recovery is actual not only for heating systems and for trains, it has been investigated as possibility to supply energy-efficient air conditioning to transport vehicles [7], as currently air conditioning has relied on either direct mechanical power from diesel engine to drive compressor (mostly found in cars) or electrical power to drive distantly located conditioning units (mostly on trains, trams), both having a long chainage of power transmission.

3. HEATING SYSTEMS FOR DMU TRAINS AND OVERALL REQUIREMENTS

In this article, a heating system and its control algorithm is reviewed, as developed for compliance to the standard EN 14750-1 “Railway applications - Air conditioning for urban and suburban rolling stock - Part 1: Comfort parameters” [18]. Before going into details of the heating system and its algorithm, a brief overlook in the main requirements of the standard for the DR1AC train in question – designed as A category (suburban) – heating mode, is as follows:

1. Recommended interior temperature setting - $+21^{\circ}\text{C}$, allowed range $+19^{\circ}\text{C}$ to $+22^{\circ}\text{C}$, irrespective of outer air temperature, as long as it stays in the range of -40°C to $+15^{\circ}\text{C}$;
2. Mean interior temperature, measured across the whole passenger compartment, must not differ from interior temperature setting by more than 2°C ; difference of highest and lowest temperature – not more than 4°C .
3. Maximum allowed air speed in the passenger interior – $0,2\text{ m/s}$, if mean interior temperature is below $+21^{\circ}\text{C}$ and gradually rising to 0.4 m/s at $+24^{\circ}\text{C}$.

4. Minimum fresh air supplied to the passengers – 15 m³/h per person, allowed to be reduced till 10 m³/h per person when the heating system is operating at its limits.
5. Maximum temperature of hot air diffused on a seated passenger - +45°C.

There are several main types of heating systems used in diesel multiple unit trains, to be grouped in such groups:

A. Heating systems using diesel engine jacket water as heat source

Main drawback of these systems – amount of heat available for heating purposes depends on the load of the main and/or auxiliary diesel engine, and this in turn depends on the timetable, route profile and driving style of the driver. Heat can be delivered to the passenger compartment in two ways – by water radiators (supply of heated fresh air done separately), or by using water-to-air heat exchangers, delivering heated fresh air as the primary heating means. In case of train consisting of several carriages, supply by coolant is not practical, owing to long piping and risks of leaks, inconvenience of system fill-up/drainage during recombination of train consist. Heating by supply of hot air has been successfully implemented for multiple carriage consists, without restrictions for carriage recombination, but with their own drawbacks – as the train consist gets longer, hot air cools substantially before reaching the last passenger compartment. Other drawbacks of hot air system will be analyzed further in details from the service experience of DR1A and DR1B trains later.

B. Heating systems using autonomous diesel fuel heaters as heat source.

These systems utilize small diesel fuel heaters (Webasto, Eberspaecher, etc.) to deliver heat to the passenger compartment either as heated outside air, or as heated cooling liquid. These systems burn additional diesel fuel, thus increasing the fuel consumption, but the increase is marginal due to the fact that these fuel heaters are very efficient (>80%). They can be installed as well in carriages without diesel engines, but this implies the consequences of having independent diesel fuel tank and piping in every carriage.

C. Heating systems using electricity supplied from main or auxiliary generator (driven by diesel engine). These are the most flexible heating systems, can be easily controlled and do not require additional external systems (as cooling piping or diesel fuel systems), but are the most fuel inefficient way owing to long chainage of power transmission. Another version of heating as per this group is utilization of heat pumps (air conditioning units working in reverse) to supply heated fresh air in cold season. Systems of this group cause additional load of the diesel engine, which results in wear and decreased service life, but for the rolling stock designer. they are the simplest solution, especially in the case if the train in question is to be equipped with auxiliary generator feeding air conditioning, thus there is plenty of power available to be used for heating in cold season.

Utilization of engine waste heat for heating purposes, especially in case of trains consisting of multiple coupled carriages divided in several compartments, has been a complicated task. So far, the author knows only two DMU train producers, which have used these systems in series design with success, in both cases utilizing hot air heating. Overall description of the trains and heating systems can be found in Лернер et al [28]; the rest of the notes and observation given further come from author's first-hand experience with trains produced by Riga Carriage building plant.

3.1. DR1A series diesel trains built by Riga Carriage building plant (1976-1998)

DR1A series DMU trains were built in Riga, Latvia, as successors to the DR1 and DR1P series, with only slight principal changes as regarding the heating system. The heating system utilized heat from diesel engine cooling water, by diverting the water in a parallel route to two saloon heating radiators (water-to-air heat exchangers) located in the middle of the motor carriage, just above the middle vestibule. There air was sucked from outside by two centrifugal blowers mounted on a single direct current (DC) motors shaft, passing through air filters and through saloon heating radiators, and further being pumped into main ventilation duct, located in the ceiling of the passenger compartment, and running through all train carriages, with flexible bellow ducts at the train coupling area. Regulation and control of heating system was carried out by several means:

1. If diesel jacket water temperature was below $+80^{\circ}\text{C}$, a pneumatically actuated valve closed water circuit to the cooling block, leaving only small water flow to prevent freezing of radiators. This in turn forced the entire cooling water flow to pass through saloon radiators, for maximum waste heat recovery, but in actual winter operation, this resulted in situations when the engine was overcooled. Interior temperature indirectly was linked with the service the train was working – express trains had plenty of heat, whereas slow stopping trains could struggle to heat up the passenger consist, leading to passenger complains.
2. In case if all passenger interiors' temperature increased to more than $+19^{\circ}\text{C}$, pneumatically actuated air flaps were opened, which allowed the fresh outside air to bypass saloon heating radiators and to be sucked by the blowers and pumped in the central air duct without heating, thus resulting in decrease of temperature in passenger compartments. Owing to the substantial thermal inertia of air ducts, the change of supplied air temperature was not that sudden, as the radiators seem to create full bypassing. When the temperature decreased below $+19^{\circ}\text{C}$, the flaps would be closed again and the process repeated.
3. Supply of hot air from one motor carriage was used to supply three passenger compartments located in a half consist of a six-carriage train or all four passenger compartments of the three-carriages consist. To regulate supply in each of passenger compartments, adjustable flaps were installed in the vertical air ducts branching from the main air duct, but these required manual adjustment and were not adjusted apart from initial setup at factory. Owing to substantial decrease of hot air temperature along the main air duct, passenger compartments located further away had increased air supply amount of less temperature, and vice versa – the passenger compartment of motor carriage was the most prone to overheating, thus were limited in fresh air supply. This **resulted in the contradiction of air supply** – if fresh, hot air was supplied evenly to all compartments, temperatures were not distributed evenly, and vice versa – attaining similar temperatures in all compartments meant that first half of the consist had significantly less fresh air.
4. In the centre of each passenger compartment, an electrical heater was installed of 8 kW power, to be used during train standby and preheating, and which could be used under motion as well, but in reality, these heaters were underpowered in comparison to the heat losses and could not cope in case of significant lack of heat from engines. Total installed heater power was 48 kW for a six-car consist. If used for preheating from external source (110 V DC), control was by on-off logic with threshold value of $+13^{\circ}\text{C}$.

Diesel trains DR1A were thoroughly tested during Soviet period in all operational conditions, including in severe cold conditions, and the results obtained in these tests concluded that the heating system and its control in average conditions could ensure mean interior temperature of $15\pm 3^{\circ}\text{C}$ with outside air temperature as low as -40°C , but with strong correlation with the load of the diesel engine.

It is interesting to note that during overall heating system tests on DR1-009 train in the arctic areas of Labytnangi and Vorkuta, Russia, a hot air heating system by extracting heat from exhaust gases by full flow air-to-air heat exchanger was tested, but the results were unsatisfactory – during idling and low load, no significant heat could be extracted from exhaust system due to low thermal inertia, and vice versa – at full load the hot air temperatures exceeded 200°C and the service life of the heat exchanger was very short.

In comparison to nowadays requirements of articles [18-19], it can be concluded that design of DR1A trains could not solve several serious issues:

- lack of heat for heating purposes owing to unregulated and unpredictable operational conditions, with impossibility to reach required interior temperature;
- contradiction in requirements of temperature and fresh air adjustment between different passenger compartments, not solvable by simple manual adjusting flaps;
- crude control logic (on-off, without hysteresis), coupled with substantial thermal inertia of the systems involved, resulting in fluctuating passenger interior temperature, risk of overcooling of diesel engine.

Despite these design shortcomings, many DMU trains of DR1A series or their derivatives (DR1AM, etc.) are still in operation in Latvia, Lithuania, Russia, Belarus, Ukraine and elsewhere.

3.2. DR1B series diesel trains built by Riga Carriage building plant (2005-2009)

In 2005, a modernized design (series DR1B) was built for Belarusian railways in several versions of six- and three-car consists. In terms of heating system, these trains had slight alterations:

1. Temperature sensors and control elements were replaced by more modern systems, increasing reliability. Control logic itself was not changed; the limit for allowed lower interior temperature was first raised to +16°C and then to +20°C;
2. Electric blowers were provided for additional heating of the passenger interior during motion (2 in motor car and 6 in each intermediate car, 2 kW each with total power of 56 kW for six cars consist), but still limited owing to the available auxiliary generator power. Control logic was on-off with the temperature threshold of +19°C.
3. Passenger compartments were supplied with electrical heaters (tubular electrical heaters installed in the air supply vents) of 28.8 kW total power for a six-car consist for standby heating from grid. These heaters could not be operated from trains on board generators, but they were installed to ensure maximum preheating of carriages at standby, for easier maintaining of heated passenger compartments during operation;
4. Preheating of the passenger compartments was facilitated with the allowed use of “stop-regime”, when the train is set on brakes and the hydraulic transmission is engaged, resulting in conversion of all mechanical energy generated by the diesel engine into heat released in the hydraulic transmission oil, which was transferred to the engine cooling liquid by the oil-to-water heat exchanger and later delivered to the centralized heating unit. “Stop-regime” was allowed to be used for low engine rpm, corresponding to approximately 22% of the rated power at full speed.

During certification of the trains, extensive testing was done on the heating systems, first in 2005, and then a scheduled recertification was carried out in 2008-2009. As the requirements of Belarusian railways were more relaxed than for example those of Latvian [18], certification was successful, but at the same time, valuable material was collected for further development of heating system.

For example, during a brake certification test run, which consisted of sequential full acceleration - full service brake rounds, parallel factory testing of heating system was carried out in conditions of plentiful waste heat available for heating, with mild outside air temperature conditions. Several positions of air flaps were tested, regulating the flow of hot air to the different passenger compartments, and results of two such tests are shown in Fig. 1 and Fig. 2. As it can be seen, the distribution of air flow and temperature level between passenger compartments is very sensitive to air flap positioning, with the whole system redistributing air flow under change of any one air flap.

3.3. D1 series diesel trains built by Ganz-Mavag factory (1964-1988)

The DMU trains built by Ganz-Mavag factory in Hungary are similar in terms of design of heating system. The difference is in the air supply – D1 series diesel trains have three main air ducts in the ceiling area, with one central air duct serving as a recirculation air duct, and the air fed to the two-side air ducts is a mix of fresh outside air and hot recirculated air. It must be noted here, that in DR1A series trains, a slight phenomenon of similar recirculation has also been noted, by air being sucked in the central ventilation unit through clearances in interior and ceiling panels but estimated not to exceed 10% of fresh air supply and increasing in case of clogged fresh air filters.

A substantial difference of D1 trains is that they are equipped with electric servo motor-driven water regulation valve, which has internal control circuit. This control circuit is fed by input signal in means of temperature of recirculating air extracted from passenger compartments, and the reference value to be achieved by the controller is set at 20°C. Thus, the D1 trains have more advanced control logic with less risk of temperature fluctuations.

D1 trains were built mostly as four-car consists (but six-car consists were operated too), with two motor carriages, thus each motor carriage usually supplied heat only to two carriages - two passenger compartments, with shorter air ducts than in DR1A trains. Division of fresh air/heat supply to passenger compartments was in a similar way – with flaps in vertical air ducts branching from the supply air ducts.

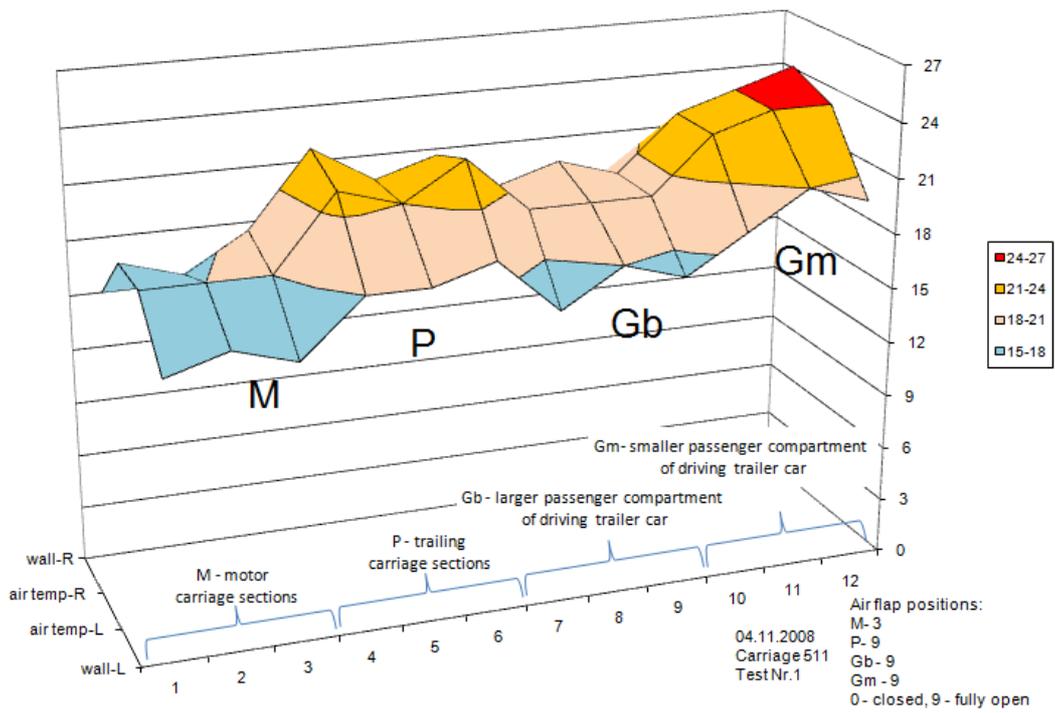


Fig. 1. Distribution of passenger compartment mean interior temperatures along the three carriages consist, train DR1B-511, test Nr.1 carried out on 04.11.2008 with outside air temp. of +2°C

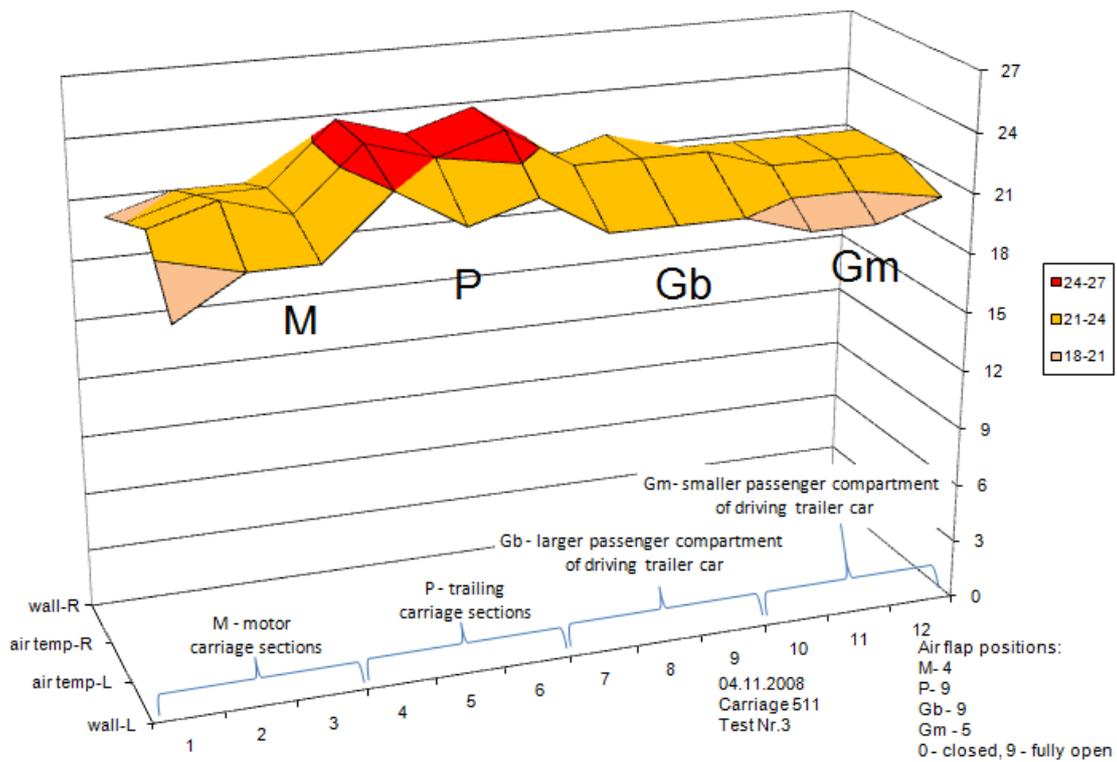


Fig. 2. Distribution of passenger compartment mean interior temperatures along the three carriages consist, train DR1B-511, test Nr.3 carried out on 04.11.2008 with outside air temp. of +2°C

D1 trains were also less powerful, having 2x538 kW for four-car consist, weighing 210 tons empty and 274 tons loaded, giving specific power rating of 5,12 kW/ton empty and 3,92 kW/ton loaded. In comparison, DR1A train had 2x736 kW for six-car consist of 272 tons empty and 352 tons loaded, resulting in 5,41 kW/ton empty and 4,18 kW/ton loaded; thus, for similar operational timetable conditions, D1 trains were “worked harder”, and had more heat available for heating. This is especially the case for six-car D1 consists, which despite the longer air ducts and heat losses in three carriages, had to sustain high power for substantially longer time, to achieve acceptable acceleration rates; thus, the problem with lack of waste heat is less important on D1 trains. No supplemental electrical heaters were installed in the passenger compartments; thus, D1 train heating systems are not hybrid systems.

At last, it must be noted that the electrical blowers used for supply of hot air had three speed steps – 870, 1000 and 1500 rpm – and the speed was regulated according to outside air temperature. This even further allowed to decrease supply of air in case of cold outside air temperature, thus minimizing heat necessary to heat it up to the supply temperature, but at the expense of even further reducing fresh air supply to passengers.

4. HEATING SYSTEM OF THE MODERNIZED SERIES DR1AC DMU TRAIN

In the contract for deep scale modernization of DMU trains for Latvian railways, to be named series DR1AC, it was obligated to attain full conformance to standard EN 14750:2006 requirements. With the historically known shortcomings of heating system in DR1A series trains, and as well with the experience gained with DR1B trains, it was concluded that several influential changes in the heating system must be incorporated:

- hot air heating system is to be utilized for maximum waste heat recovery till the extent possible, in the mean time preventing overcooling of the diesel engines;
- for stable operation of diesel engines (main traction engine and auxiliary diesel-generator), cooling system circuits were to be separated between themselves and the saloon heating system, with transfer of heat through parallel connection water-to-water heat exchangers and electric liquid pumps;
- in case of lack of heat from both diesel engines, an autonomous Webasto diesel fuel heater of 35 kW power installed for engine preheating was also used as the third heat source during the motion of the train;
- for control of total amount of fresh air supplied to the passenger interiors in relation to the outside air temperature, a frequency inverter-driven centrifugal air blower was installed;
- owing to significant auxiliary power available from diesel-generator, all passenger compartments were supplemented with electric hot air blowers, to be used both for preheating and standby heating, and as well for additional heating during motion. The total installed heating power in passenger compartments equals 62.5 kW for a three-car consist.

The principal layout of heating system components and air ducts is illustrated in Fig. 3. The simplified scheme of both cooling systems and passenger compartment heating system is illustrated in Fig. 4.

To facilitate preheating, simultaneous use of hot air heating system and all installed electrical heaters is allowed. In preheating mode, the electrical heaters are operational until +15 °C is reached in the passenger compartment, and further control is by on-off regime at the threshold value.

In the DR1AC trains, a Voith gearbox is installed, which allows higher heat dissipation than the original Kaluga machinery plant built one for DR1A; thus, the allowed range for “stop-regime” (see description in chapter on DR1B trains) is extended to engine rpm of 800 to 1500 rpm (from maximum 1900 rpm). Thus, the maximum load exercised by the hydrodynamic transmission is approximately 49% of the engine’s rated power.

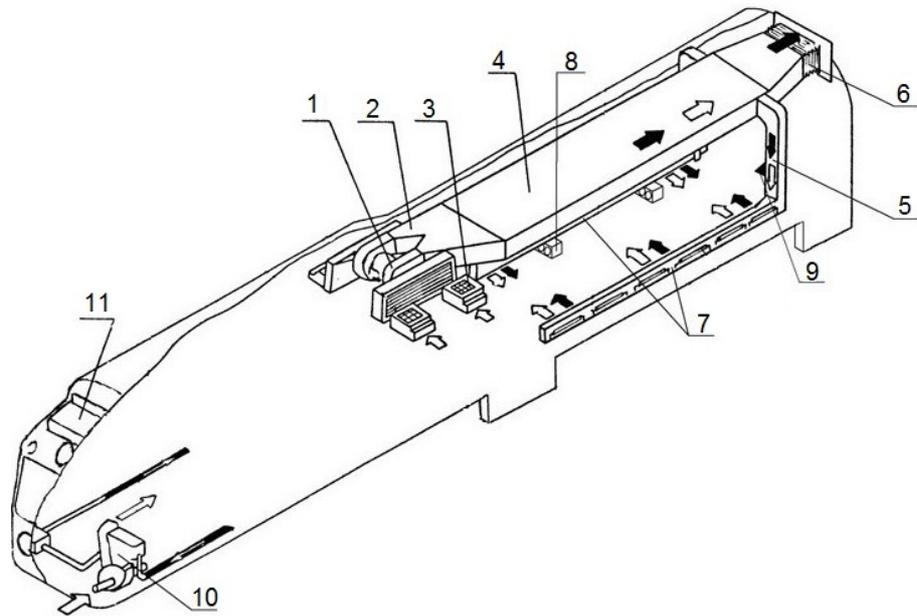


Fig. 3. Overall view of heating system of DR1AC train motor carriage, reproduced from [8]. 1 – centrifugal air blower, 2 – connecting air ducts, 3 – fresh air filters, 4 – main air duct, 5 – vertical branch air ducts, 6 – flexible air ducts for coupling between carriages, 7 – horizontal air ducts for distribution of hot air, 8 – electric blowers, 9 – air flaps, 10 – cabin heater, 11 – cabin air conditioner

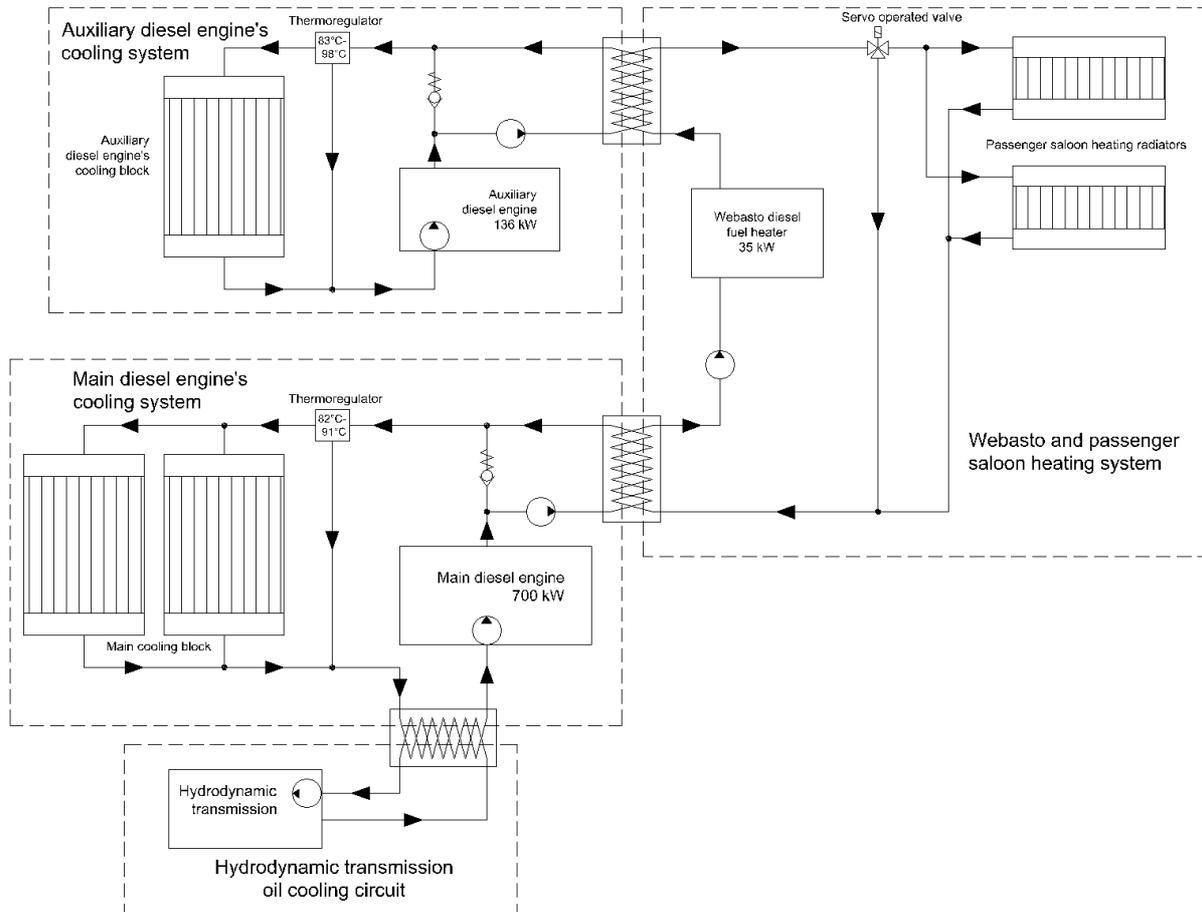


Fig. 4. Simplified hydraulic scheme of main and auxiliary diesel engine cooling systems and Webasto & passenger saloon heating system of the DR1AC series modernized DMU train.

5. HEATING SYSTEM'S CONTROL ALGORITHM ON SERIES DR1AC TRAINS

As the heating system itself has manifested in a complex system, having controllable (electric blowers, Webasto heater) and uncontrollable (both diesel engines) heat sources, with many elements to be controlled, the design required an elaboration of a sophisticated train interior heating system control algorithm.

As previously discussed, the air flaps installed in vertical air ducts were manually adjustable, and they simultaneously redistributed both flow of fresh air, and as well the amount of heat supplied to each passenger compartment. As the heating system must maintain and control stable and uniform interior temperature, without affecting minimum flow of fresh air, it is logical to set up position of air flaps only according to the necessary distribution of the fresh air (done once during factory testing), and to be locked in the position to safeguard from tampering.

Algorithm developed focuses on three main controlling objects:

1. regulation of liquid flow in the saloon heating radiators, by the aid of electrical servo-driven three-way valve, redistributing flow either through the radiators or through a bypass, and control logic consists of proportional-integral regulator;
2. control of individual electric blowers in passenger compartments, to maintain necessary temperature in each compartment and to supplement heat lacking from the hot air heating system, and control logic consists of proportional-integral regulator adjusted for stepped output signal and minimum switching of electrical blowers;
3. control of volumetric fresh air flow rate by regulating centrifugal air blower speed by variable frequency drive. By gradually lowering the air flow rate in dependence to the outside air temperature, necessary heat balance is ensured, thus that heating of fresh outside air does not take too much heat in case of severe winter conditions, realized by simple stepped proportional control.

As simultaneous control of all passenger compartments is necessary (four compartments for the three-cars consist, as the four-cars consist has two motor carriages serving a half of consist each) and to avoid interaction between control regulators of hot air heating system and electrical blowers, control of liquid flow as per point 1 is carried out in accordance to the temperature trends in the hottest of all passenger compartments. The hottest passenger compartment is detected by utilizing mean temperature of the interior (two sensors) recorded for a minute and extrapolating the trend for a further minute of time, as the hot air system is an inertial one, and to avoid regulator fluctuations when the role of the hottest compartment is changed over from one compartment to another.

This way maximum amount of waste heat is recovered from engine cooling systems, without causing overheating in other passenger compartments. To further avoid interference between control regulators of hot air system and electrical blowers (which are supposed to supply only the missing amount of heating power), the reference value for regulators is set as " $T_{ic} + 1^{\circ}\text{C}$ " for hot air system and " $T_{ic} - 1^{\circ}\text{C}$ " for electrical blowers in passenger compartments which are not the "leading compartment" (i.e. the hottest one), where T_{ic} – interior temperature setting. In the hottest passenger compartment, which is the feedback source for the hot air heating regulator, the electrical blowers are used only if temperature is more than 2°C below T_{ic} , which corresponds to the case that hot air system is not capable to maintain stable conditions alone (especially during preheating stage).

Control of individual electric blowers in passenger compartments is carried out separately for each compartment, as these blowers are circulating only internal air, and thus their influence on the gradient of interior temperature can be easily predicted and controlled.

More minor control elements of the algorithm are implemented for control of engine heat regime, for example, electric coolant pumps for takeoff of heat from main diesel engine cooling circuit are turned on only if the coolant temperature is above $+60^{\circ}\text{C}$, thus avoiding overcooling of the main engine. Overcooling of the auxiliary engine is avoided by automatically turning on Webasto diesel fuel heater, if temperature of the coolant in Webasto circuit falls below $+75^{\circ}\text{C}$, and turned off when it exceeds 80°C , to avoid unnecessary usage of Webasto heater when enough heat is available from diesel engines.

Overall view of measuring points of different air temperature sensors used in the control algorithm is given in Fig. 5.

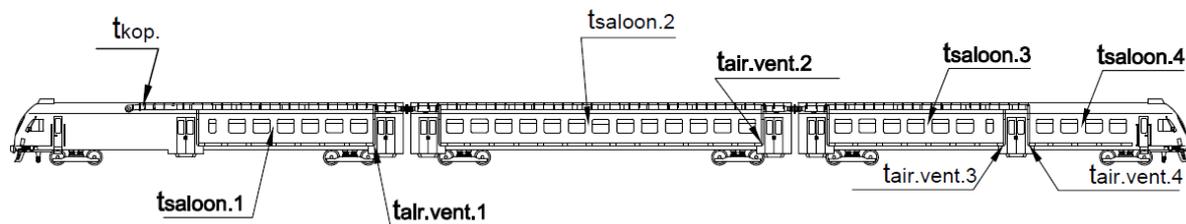


Fig. 5. Overall view of internal measuring points for the heating control system

Temperature of hot air supplied to the passenger interior is controlled in the vertical branch air ducts, just before entering the horizontal diffuser air duct. In case if the temperature of the hot air exceeds $+45^{\circ}\text{C}$ (maximum allowed by [18]), coolant flow is reduced accordingly to maintain $+45^{\circ}\text{C}$. This way it is possible to use even higher hot air temperatures in the main air duct, ensuring that maximum heat potential is provided so that the last of passenger compartments are supplied with as much heat potential as possible. During trials it has been also observed that high temperatures of air in the exit from heat exchangers ($>60^{\circ}\text{C}$) also help to heat up the main duct, while at the same time air delivered to the last passenger compartments is in the range of $+25$ to $+35^{\circ}\text{C}$, thus well below the limiting $+45^{\circ}\text{C}$.

6. FACTORY AND HOMOLOGATION TEST RESULTS OF SERIES DR1AC TRAINS

The designed heating system and its control algorithm was tested on the first modernized train DR1AC-219.1 first in factory testing conditions and then passed over to homologation tests. Initial set-up of the heating system included necessity to adjust few parameters:

- a) regulation coefficients of the PI regulator of cooling liquid flow to the hot air heating radiators;
- b) temperatures of fire-up and shut-down of additional Webasto diesel fuel heater;
- c) volumetric flow rate of the central heating unit's air blower;
- d) position of air flaps in the vertical branch ducts at the entrance to each passenger compartment; and
- e) threshold values for switching on-off of passenger compartment heating blowers.

From these, it was concluded that parameters a), b) and e) were defined successfully by "intelligent guess" during the design stage and no adjustment is necessary. Parameter c) needed to be determined during testing, as the exact total hydraulic resistance of the air duct system, was unknown, and no exact value of blower shaft speed could be determined at the design stage. Parameters c) and d) were interrelated, as adjustment of air flaps changed the total hydraulic resistance of air ducts and redistributed hot air flow between all compartments.

Factory testing of the saloon heating system commenced without any significant problems; the only problems experienced were related to the assembly quality of the central air ducts and passenger interior, to minimize air leaks which were jeopardizing the distribution of air flow.

Results of one of the tests for driving trailer car are reproduced in Fig. 6. As can be seen, the results are very satisfactory. The jig-saw profile lines Nr. 10 and 22 correspond to the top of the both passenger compartments and illustrate how periodically electrical heaters were cycled by the algorithm for heat supplementation, as this carriage is the most distant from motor car and has the lowest temperature of supply hot air. On average, the wavelength of line Nr. 10 for 2nd class compartment is 27 minutes, and for the line Nr. 22 for 1st class compartment – 40 minutes, indicating steady-state conditions in the compartment.

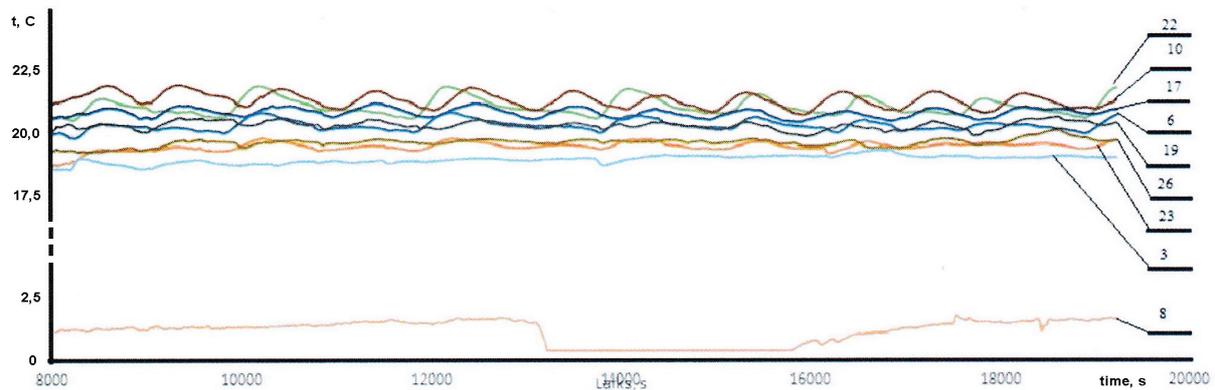


Fig. 6. Testing results for the driving trailer car DR1AC-219.8 both passenger interiors, January 2016, results reproduced from [9]. Testing in standstill inside factory premises. Lines: 3 – temperature in middle vestibule, 6 – 2nd class compartment left side middle height, 8 – ambient air temperature, 10 – 2nd class compartment top, 17 – 1st class left side middle height, 19 – 2nd class compartment middle, 22 – 1st class compartment top, 23 – 1st class compartment bottom, 26 – 2nd class compartment bottom

7. CONCLUSIONS

The modernized series DR1AC DMU trains have been supplied with plentiful heating power from different sources (main diesel engine cooling water, auxiliary diesel engine cooling water, Webasto diesel fuel heater, and electrical blowers, and indirectly also from hydrodynamic transmission cooling oil), ensuring successful fulfilment of standard [18] requirements irrespective of the operational conditions and the load on the diesel engines. The designed heating system uses different heat sources in the preference of their efficiency, thus minimizing the cost of comfortable interior conditions in the terms of fuel consumption. For example, especially during preheating of the train consist, when the diesel engines are not heated up or are idling, increased use of electrical blowers causes short-term increase in loading of auxiliary diesel generator, which in effect results in increase of heat dissipated in the cooling system of the auxiliary diesel engine. This additional heat is uptaken by the hot air heating system in preference and delivered to the interior; thus, the electrical heating is used only as the last resort, to supply missing heat in the minimum necessary amount.

In stabilized conditions, the electrical heating is used to supplement only the minimum amount of heat missing from other sources, and to balance each passenger compartment individually, thus maximum energy efficiency is achieved. As indicated during factory testing, cycle times for supplementation of missing heat are as high as 27 – 40 minutes, indicating good steady conditions of passenger compartment achieved mainly owing to the systems' thermal inertia.

Thus, although the heating system and its control algorithm might seem complicated, the increased capital costs during the modernization are to be outweighed by operational benefits of decreased fuel consumption and increased service life of both diesel engines. In conclusion, the author wishes to stress that every comparison between different systems must be done on equal outside and internal conditions, for example, during start of the operation. The modernized DR1AC trains were found to be consuming more diesel fuel in comparison with the DR1A trains. This is true taking into account that the modernized trains have been supplied with extra equipment (diesel generator, onboard WC, air conditioning, etc.) increasing train tare weight by far more than the increased efficiency gain from installed modern diesel engines. This increase in fuel consumption cannot be related to the heating system either, as the original DR1A series diesel trains were economical not because of their simpler heating system but because of their design incapability to fulfil modern train heating interior standard [18] requirements.

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