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THE INFLUENCE OF FUEL COMPOSITION ON THE OPERATING CHARACTERISTICS OF THE STEAM BOILER

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Abstract

The paper presents the impact of using high ash content and poor heating value hard coal as fuel for a steam boiler. As expected, the poor quality of the fuel has an important impact on the efficiency of the steam boiler, reducing it by almost 4%. From that also results an increase in specific fuel consumption of the boiler. The mechanism by which these negative results are reached are mainly the increase in losses through combustion gases by nearly 2% and the heat of the evacuated slag which almost doubles.

Keywords: *heating value, boiler efficiency, specific fuel consumption.*

1. Introduction

A less mentioned component of the current energy crisis is the availability of energy sources. It is now of greater significance due to the effects of war in the eastern European region.

Due to the drop in production in some regions, the uncertainty of trade routes and the resulting increase in logistical problems are making it difficult to obtain energy sources.

For example, in the case of coal needed to operate thermal power plants, it will become necessary to find other suppliers due to interruption of the supply chain from certain sources.

Since the coal may now come from different mining sites each time, its composition and calorific value will also change.

As is well known, coal with a low calorific value provides little heat and, as a result, more of it is consumed. Improperly selected coal does not burn properly, falls off the grate unburnt and, despite its high calorific value, also provides low performance with high consumption.

The calorific value of coal, and also its composition, affects the efficiency of the steam boiler. So, in order to get an accurate idea of how the quality of the fuel affects the efficiency of a steam boiler, an energy balance must be performed.

The aim of this paper is to shed light on the efficiency of a steam boiler dependent on the use of coal with different calorific values, as a result of performing energy auditing.

With conclusions resulting from analyzing different indicators of a steam boiler operating at different loads and coal composition, specialists can assess the extent of possible losses even before the fuel is used, and can take measures to reduce them.

It is also possible to identify the effects of different coal composition on the efficient operation of the boiler, which are not obvious at first glance.

2. Steam boiler configuration and technical data

Modern high-efficiency power plant boilers all produce superheated steam and use water-tube boilers for this purpose.

The purpose of steam boilers in power plants is to produce superheated steam from the supplied feed water.

The construction of a typical water tube boiler is shown in Fig. 1. Here can be seen the main structural elements of the steam boiler: Steam drum or boiler drum - for separation of water and steam. Dry, saturated steam leaves the boiler drum. Boiling pipes and downpipes – which, together with the supply pump, ensure circulation. Steam superheater - for superheating the steam coming from the drum to a given temperature. The feed water pre-heater heats the supplied feed water to a temperature approaching the boiling point. The air heater preheats the combustion air.

The rated output of the steam boilers in power plants is a few hundred tons of steam per hour, and accordingly, the fuel consumption is also high, exceeding one hundred tons per hour.

In the case of this type of steam boiler, according to law, energy audits must be carried out at certain intervals.

Auditing must be carried out in accordance with standards and a large number of specialized publications are available allowing users to properly conduct energy audits **[1–7]**.

On the occasion of the modernization of the nearby thermal power plant, between 2000 and 2007, a new boiler was installed in place of the old one, of the Ramzin type, and since then it has passed the energy audit procedure and the evaluation of performance indicators several times.

The energy audit is required to be carried out by authorized personnel in close collaboration with the beneficiary which usually is also the operator of the audited installation.

The nominal characteristics of the steam boiler can be found in **Table 1.**

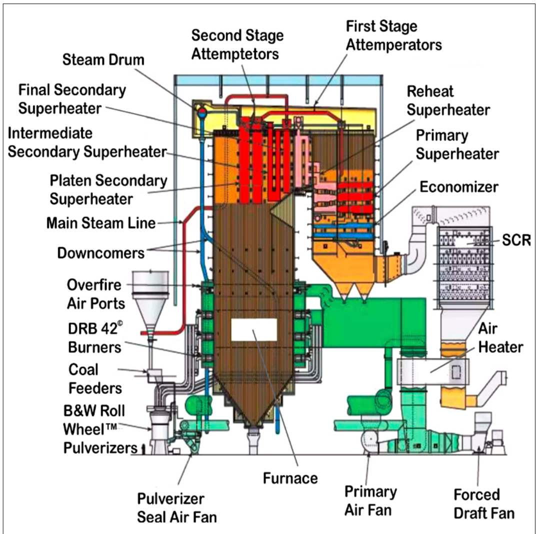

Fig. 1. *Construction of the water tube boiler* **[8]**

Table 1. *Rated characteristics of steam boiler*

Nom.	Value
Steam flow rate, t·h^{-1}	540.0
Steam temperature (for 75-100 % flow rate), °C	541.0
Steam pressure (relative), MPa	13.85
Reheat steam flow rate, t·h^{-1}	471.4
Steam temperature at reheater inlet, °C	350.7
Steam pressure at reheater in-let, MPa	3.12
Steam temperature at reheater outlet, °C	541.0
Steam pressure at reheater outlet, MPa	2.96
Feedwater temperature at economizer inlet, °C	235.4
Flue gas temperature at air preheater outlet, °C	143.0
Excess air coefficient at economizer outlet	1.20
Excess air coefficient at air preheater outlet	1.30
Rated efficiency, %	90.70

The above-mentioned steam boiler works with hard coal, and its nominal composition and calorific value can be found in **Table 2,** and accordingly the manufacturer guarantees an efficiency of 90.70%.

In order to perform an energy audit, according to current regulations, measurements must be made in three different operating modes: technological minimum, nominal and maximum load.

If it is not possible, it can be done for the smallest possible, largest possible and intermediate loads.

The calorific value of the fuel can be determined approximately based on various equations found in the literature.

Analyzing the equations, it is possible to conclude how the composition of the fuel affects its calorific value.

Table 2. *Composition of coal for rated efficiency*

Share	%
Carbon C^i	36.6
Hydrogen H^i	2.8
Sulphur S^i	1.5
Nitrogen N^i	0.7
Oxygen O^i	7.6
Moisture W^i	12.8
Ash A^i	29.6
Lower heating value 13 816.4 kJ·kg^{-1} (3 300.0 kcal·kg^{-1})	

Let us consider as a starting point the following equation [1]:

$$H_i = \frac{4{,}187}{100} \cdot \left[8097 \cdot C^i + 28690 \left(H^i - \frac{O^i}{8} \right) + 2210 \cdot S^i - 600 \cdot W^i \right] \quad \frac{kJ}{kg} \qquad (1)$$

where X_i-vel jelöljük az elemi összetevők részarányát, ahogy az denotes the proportion of components as shown in **Table 2.**

It can be clearly seen that the calorific value is higher if there is more carbon (C), hydrogen (H) and sulfur (S) in the fuel, while high oxygen content and water content negatively affect the fuel's calorific value.

In conclusion, the composition of coal affects its calorific value not only by the combustible components, so it is worth analyzing all types of energy loss that can be linked to the composition of the fuel.

After that, depending on these values, the operating characteristics of the steam boiler can be assessed.

We will start with the losses with the highest share in overall losses of a steam boiler.

According to literature [1, 9] flue gas loss is the highest Q_{gacos}:

$$Q_{gacos} = B_i \cdot (1 - n) \cdot V_{ga} \cdot i_{ga} \qquad (2)$$

B_i – denotes the fuel mass flow rate, kg·s^{-1}; V_{ga} – volume of flue gas produced for every unit of fuel m^3_N·kg^{-1}; i_{ga} – the enthalpy of the flue gas kJ·m$^{-3}_N$, where N – is a coefficient that takes into account the proportion of unburnt fuel in the slag and fly ash, %.

Further analyzing formula (2), the volumetric flow rate of flue gas can be calculated using the following equation [1, 9]:

$$V_{ga} = V_{gus} + V_{H2O} \quad \frac{m_N^3}{kg} \qquad (3)$$

where V_{gus} denotes the volume of dry flue gas produced from the fuel, m^3_N·kg^{-1}; V_{H2O} is the volume of water vapour in the flue gas, m^3_N·kg^{-1}.

In the case of solid or liquid fuel, these can be calculated using the following formulas [1, 9]:

$$V_{gus} = \frac{1}{100}\left(1{,}867 \cdot C^i + 0{,}7 \cdot S^i + 0{,}8 \cdot N^i\right) + (\lambda - 0{,}21) \cdot L_0 \quad \frac{m_N^3}{kg} \qquad (4)$$

$$V_{H2O} = \frac{1{,}244}{100}\left(9 \cdot H^i + W^i + 0{,}1 \cdot \lambda \cdot L_0 d_a\right) + 1{,}244 \cdot g_{inj} \quad \frac{m_N^3}{kg} \qquad (5)$$

where X_i denotes the proportion of coal components as shown in **Table 2**, and in addition, L_0 – the amount of air required for combustion, m^3_N·kg^{-1}, λ – excess air coefficient, d_a – moisture content of the ambient air (%).

In the case of gaseous fuel [1, 9]:

$$V_{gus} = \frac{1}{100}\left((CO_2)_c^i + (CO)_c^i + \sum m(C_mH_m)_c^i + (H_2S)_c^i + (N_2)_c^i\right) + (\lambda - 0{,}21) \cdot L_0 \quad \frac{m_N^3}{m_N^3} \qquad (6)$$

$$V_{H2O} = \frac{1}{100}\left((H_2)_c^i + \sum \frac{n}{2}(C_mH_n)_c^i + (H_2S)_c^i\right) + 1{,}244 \cdot (d_c + L_0 \cdot d_a) \quad \frac{m_N^3}{m_N^3} \qquad (7)$$

in addition to the variables denoted above, the moisture content of the fuel is denoted by d_c m^3_N· m$^{-3}_N$.

At the same time, the amount of air required for complete combustion of the fuel is calculated using the following formulas [1, 9]:

– in the case of solid or liquid fuel:

$$L_0 = \frac{1}{100}\left[8{,}89 \cdot C^i + 26{,}7 \cdot \left(H^i - \frac{O^i}{8}\right) + 3{,}33 \cdot S^i\right] \quad \frac{m_N^3}{kg} \qquad (8)$$

– in the case of gaseous fuel:

$$L_0 = \frac{1}{21}\left(0{,}5 \cdot (CO)_c^i + 0{,}5 \cdot (H_2)_c^i + \sum\left(m + \frac{n}{4}\right)(C_mH_n)_c^i + 1{,}5 \cdot (H_2S)_c^i - (O_2)_c^i\right) \quad \frac{m_N^3}{m_N^3} \qquad (9)$$

As the formulas above show, the amount of flue gas produced is greatly influenced by the composition of the fuel, which is contained within every formula, and thus impacts the heat loss through flue gas.

Since the heat loss due to flue gas, Q_{gacos} As the formulas above show, the amount of flue gas produced is greatly influenced by the composition of the fuel, which is contained within every formula, and thus impacts the heat loss through flue gas.

Since the heat loss due to flue gas, Q_{cmec}, can be calculated by the following formula [1, 10]:

$$Q_{mec} = 78 \cdot B_i \left(\frac{C_{sg} \cdot A^i \cdot a_{sg}}{100 - C_{sg}} + \frac{C_{pvc} \cdot A^i a_{pvc}}{100 - C_{pvc}}\right) \quad \frac{kJ}{h} \qquad (10)$$

where B_i *denotes the fuel mass flow rate*, kg·s^{-1}; A_i denotes the share of ash in coal %; C_{sg} and C_{pvc} are the share of carbon in the combustible material remaining in the slag and in the fly ash, while a_{sg} and a_{pvc} are the proportion of the slag and the fly ash in relation to the ash content of the fuel.

Another loss, which includes the ash content of the raw material, is the heat loss by bottom ash Q_{sg} [1]:

$$Q_{sg} = 0{,}3 \cdot G_{sg} \cdot t_{sg} \quad \frac{kJ}{h} \tag{11}$$

where G_{sg} denotes the slag mass flow (kg·h^{-1}) and t_{sg} the slag temperature, °C.

Since the data in the literature [1–6] [11] show that the share of loss due to the amount of unburnt fuel in the slag and fly ash Q_{cmec} compared to overall boiler losses is very low, hence-forth this loss will not be analyzed.

The variation of Q_{gacos} and the quantity of heat removed by hot slag Q_{sg} depending on the composition of the fuel will be studied.

In addition, the efficiency of the boiler and the specific fuel consumption, depending on fuel composition, as a result of the analysis of the formulas presented above, will be analyzed.

3. Measured data and results

During the measurements, the steam boiler was operated under the following conditions: - the mass flow rate of natural gas was determined by the operator of the steam boiler in order to ensure combustion stability, as was the number of mills required for the production of pulverized coal; - all feed water preheaters were in operation; - the boiler operated in automatic mode, the parameter values were set by the process computer; - outlet steam temperature was set so that it did not exceed 535 °C at turbine inlet; - the value of the steam mass flow rate is equal to the value of the feed water mass flow rate.

The placement of the measuring instruments in order to measure the desired data is shown in Fig. 2. (only the high-pressure turbine part (HPT) and the medium-pressure (reheat - RT) turbine part of the turbine are shown).

The energy auditing was performed on two different occasions, while on one occasion the operator performed a performance evaluation of the steam boiler. Each time, the measurements were carried out for three different loads.

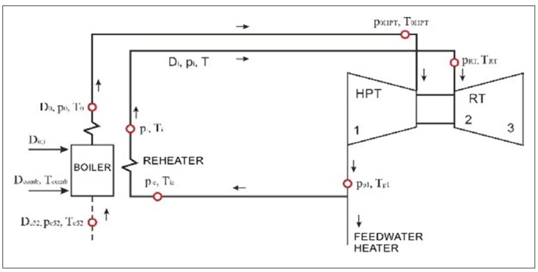

Fig. 2. *Placement of measuring instruments*

The load typically indicates the turbine load, which gave a different value each time measurements were performed.

Table 3. shows the data required for the second energy audit, and the load was as follows: minimum load: 74 MW, medium load 116 MW, and maximum load 130 MW.

Table 3. *Data required for the second energy audit*

Nom.	Minimum load	Medium load	Maximum load
Physical heat of fuel,°C	74.99	74.26	75.11
Fuel flow rate, t·h^{-1}	72.02	111.46	125.12
Methane flow rate, m^3_N·h^{-1}	2.714.2	1.785.4	1.013.7
Steam injection flow rate, t·h^{-1}	7.088	24.654	54.040
Összlevegő tömeg-áram, t·h^{-1}	375.03	518.06	589.83
Fuel composition			
C^i	0.315	0.312	0.332
N^i	0.007	0.007	0.007
H^i	0.011	0.015	0.015
S^i	0.012	0.014	0.013
O^i	0.038	0.041	0.039
A^i	0.475	0.473	0.464
W^i	0.142	0.137	0.129
Coal lower heating value, kJ·kg^{-1}	10.949	10.992	11.432
Content of combustibles in slag, %	0.47	0.49	0.51
Content of combustibles in fly ash, %	0.32	0.33	0.34
Flue gas composition			
CO_2, %	11.70	11.83	17.67
O_2, %	6.49	6.39	5.88
SO_2, ppm	1.164	1.164	1.164
CO, mg·m$^{-3}_N$	18.55	18.55	18.55
NO_x, mg·m$^{-3}_N$	143.3	143.3	143.3
Excess air coefficient in front of the air preheater	1.41	1.40	1.39
Combustion air temperature at air preheater inlet, °C	26.71	26.53	27.63

Combustion air temperature at air preheater outlet, °C	283.6	308.2	321.7
Flue gas temperature at air preheater inlet, °C	319.9	349.5	366.6
Overall temperature of flue gas at air preheater outlet, °C	153.3	164.6	173.7
Live steam pressure, bar	126.7	127.3	127.8
Live steam temperature, °C	526.9	532.7	535.0
Steam pressure at reheater inlet, bar	13.08	20.93	24.00
Steam temperature at preheater inlet, °C	315.8	340.5	350.6
Steam pressure at reheater outlet, bar	13.33	21.38	24.55
Steam temperature at preheater outlet, °C	512.2	531.2	533.6
Feedwater temperature, °C	192.8	212.4	218.1
Feedwater pressure, bar	130.0	133.7	135.6

Table 4 and Table 5 present the composition of the coal as determined during the operating performance evaluation of the steam boiler and the second audit proc.

Table 6 presents a typical energy balance table, where the different types of losses of the steam boiler are highlighted.

The share of the losses is the same as for the data found in the literature [1–6], [11]. As for the values of the losses, the heat loss through flue gas Q_{gacos} and the heat loss by bottom ash Q_{sg} are greater than expected in the case of a modern steam boiler.

Table 4. *Coal composition*

Share	**Operating performance evaluation**		
	113 MW	**130 MW**	**150 MW**
Carbon C^i	38.13	38.13	38.13
Hydrogen H^i	2.93	2.93	2.93
Sulphur S^i	1.18	1.18	1.18
Nitrogeén N^i	7.44	7.44	7.44
Oxygen O^i	0.61	0.61	0.61
Humidity W^i	7.27	7.27	7.27
Ash A^i	42.44	42.44	42.44
Lower heating value, kJ·kg^{-1}	15.638.6		

Table 5. *Coal composition*

Share	**Second energy auditing**		
	115 MW	**130 MW**	**150 MW**
Carbon C^i	43.3	41.5	41.5
Hydrogen H^i	2.8	2.8	2.8
Sulphur S^i	1.65	7.6	7.6
Nitrogeén N^i	0.7	0.7	0.7
Oxygen O^i	7.6	1.5	1.4
Humidity W^i	10.5	10.5	10.5
Ash A^i	33.45	35.4	35.5
Lower heating value, kJ·kg^{-1}	16.169.4	15.545.6	15.533.0

Table 6. *Actual hourly energy balance at 74 MW load*

INPUT		
Nom.	**MJ·h^{-1}**	**%**
Chemical heat of fuel, Q_{cBi}	856 309.18	78.88
Physical heat of fuel, Q_B	7 582.56	0.70
Physical heat of feedwater, Q_a	214 330.63	19.74
Physical heat of combustion air, Q_L	7 408.30	0.68
TOTAL INPUT (Q_i)	**1 085 630.67**	**100.00**
OUTPUT		
USEFUL HEAT		
Heat of produced steam, Q_D	885 942.00	81.61
Heat recovery by reheating, Q_{sci}	94 429.93	8.70
Total useful heat, Q_u	980 371.93	90.31
LOSSES		
Heat loss due to the amount of unburnt fuel in the slag and fly ash, Q_{cmec}	1 287.43	0.12
Chemical incomplete combustion, Q_{cga}	56.45	0.01
Chemical incomplete combustion, Q_{gacos}	77 446.03	7.13
Heat loss by bottom ash, Q_{sg}	20 581.59	1.89
Heat loss by bottom ash, Q_{per}	8 126.64	0.75
Unaccounted losses, ΔQ	-2 239.40	-0.21
Veszteségek összege, Q_p	105 258.74	9.69
TOTAL LOSS (Q_e)	**1 085 630.67**	**100.00**

4. Conclusions

In order to analyze the data, they are presented graphically.

In **Fig. 3** the efficiency of the steam boiler, η_{tb} [%], is shown as a function of live steam flow rate.

In Fig. 4 the specific fuel consumption of the steam boiler b_c g·kg^{-1}(steam), is presented as a function of live steam flow rate.

In **Fig. 5** the heat loss through flue gas Q_{gacos}, while in Fig. **6** heat loss by bottom ash Q_{sg} is shown as a function of live steam flow rate.

It should be mentioned that the identifier 1 represents data calculated in case of the evaluation of performance indicators, while the numbers 2 and 3 represent the energy auditing activities performed on the other two occasions.

Tables 3 and **4** clearly show that the average lower heating value of the fuel was the highest during the evaluation of the performance indicators (except in the case of the second audit, at a load of 115 MW), then it was lower during the first audit, reaching the lowest values during the second audit.

It must be mentioned that coal from the Jiu Valley was used every time.

Taking into account the aforementioned, the figures clearly show that the indicators are directly proportional to the average lower heating value of the fuel, the better the heating value, the better the indicators (efficiency of the steam boiler - η_{tb} %, **Fig. 3**, and the specific fuel consumption - b_c g·kg^{-1} (steam), **Fig. 4**).

In the case of losses, the influence of the calorific value can also be seen, as the losses are inversely proportional to the average lower heating value of the fuel, the better the fuel heating value, the smaller the loss Q_{gacos} [%] due to the flue gas, **Fig. 5**; and heat loss by bottom ash Qsg, [%] **Fig. 6**.

Several conclusions can be drawn based on the data presented in the figures, and these are detailed below. There is an obvious correlation between the calorific value of the fuel and the efficiency of the steam boiler, as shown in **Fig. 3**. Good quality fuel with high heating value can improve the efficiency of the steam boiler by nearly 4%, which is not negligible.

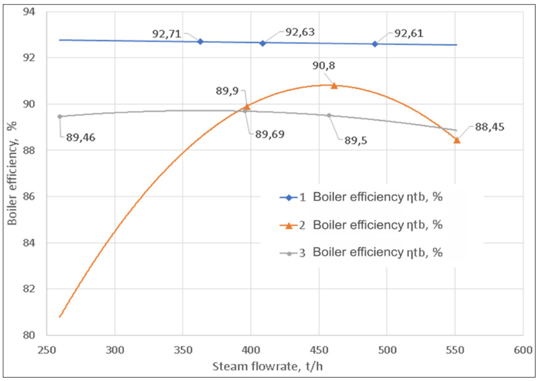

Fig. 3. *Efficiency of steam boiler.*

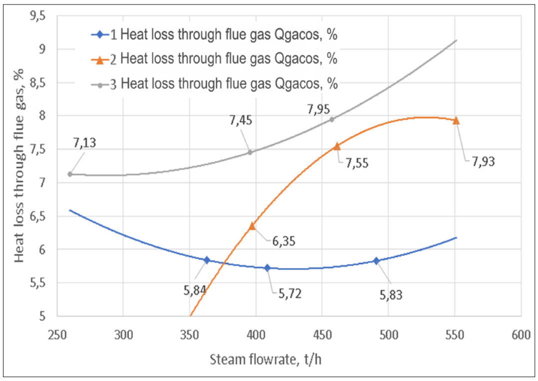

Fig. 5. *Heat loss through flue gas.*

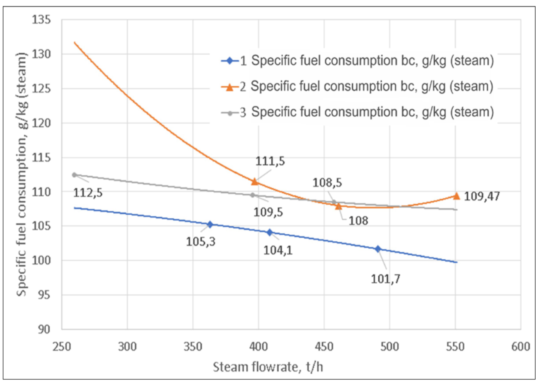

Fig. 4. *Specific fuel consumption.*

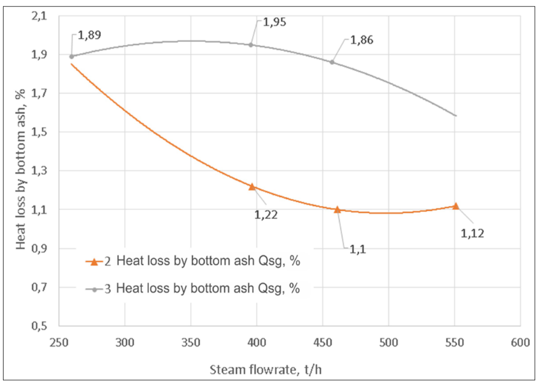

Fig. 6. *Heat loss by bottom ash.*

The specific fuel consumption, **Fig. 4**, confirms the conclusions drawn above, because, as expected, high-quality fuel results in lower fuel consumption, so the fuel costs are proportionally lower.

Fig. 5 and **Fig. 6** highlight the way that the quality of the fuel affects the losses and thus the efficiency indicators of the steam boiler. As can be seen, heat loss due to the flue gas is inversely proportional to the quality of the fuel.

The difference between the maximum and minimum values reaches 2%, which does not seem like much, but based on the data shown in **Table 6** the approximate value of this can be calculated, which in the case of the presented steam boiler is 21.724 $MJ \cdot h^{-1}$.

As for the loss by bottom ash, it was not calculated during the performance indicator evaluation, but it was calculated on the following two occasions.

It is clear that the value of this loss is almost double, since the ash content of the fuel is much higher. This loss does not directly depend on the heating value of the fuel, rather it is directly proportional to its ash content.

Of course, fuel with a high ash content usually has a lower carbon content and, depending on this, a lower heating value.

In summary, the use of high-quality fuel with a high heating value has a positive effect on the efficiency indicators of the steam boiler, reducing losses and fuel costs.

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