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**THE STIRLING ENGINE—AN OPTION
FOR UNDERGROUND MINES**

By

W. F. Marshall

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Bartlesville Energy Research Center
Department of Energy
Bartlesville, Oklahoma

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W. F. Marshall¹

ABSTRACT

The use of heat engines for powering mobile equipment in underground mines offers advantages over electric power in terms of mobility and electric shock hazards. However, exhaust is discharged into the working environment; thus there is a potential hazard associated with toxic combustion products. Although diesel engines are in use in underground mines, other heat engines might be considered for use because of potentially lower emission rates.

The Stirling engine is a possible alternative to the diesel because it shows promise as a low emission, high power density engine. In order to assess the potential of the Stirling for mining applications, performance data are required. To fill this need, data on the composition of the exhaust from a Stirling engine were obtained. The results of this work indicate that the Stirling engine compares very favorably with "low emission" diesels with respect to emissions characteristics.

INTRODUCTION

Systems used for powering equipment in underground mines include electric motors (battery and cable powered) and diesel engines. Diesel engines are widely used in non-coal mines and are being considered for increased use in coal mines. The substitution of diesels for electric motors does offer both advantages and disadvantages; for example, diesel-powered equipment has much greater mobility and presents no hazards associated with high voltage. However, because the exhaust from a diesel is discharged into the working environment, there are potential hazards from toxicants in the exhaust. Exhaust-treatment systems are available (and in use) which tend to decrease the quantities of some of the toxicants discharged, but these exhaust-treatment systems do not reduce levels of all toxicants, and their performance can degrade with time. In fact, it is possible for an exhaust-treatment system to cause increased emissions of some toxicants. Two examples of this possibility are as follows:

¹Mechanical engineer.

1. Increased production of sulfates by catalytic reactors.
2. Increased particulate levels due to increased exhaust backpressure caused by "fouled" exhaust-treatment systems.

Thus, the availability of an engine system having advantages over diesel engines with respect to emissions would show potential for use in underground mines. Lower emission levels would result in decreased potential for hazard due to exposure to toxicants and, if levels were sufficiently low, would alleviate the need for additional emissions-control equipment.

The Stirling engine appears to have potential for achieving extremely low or, in the case of a stored heat system, zero emissions. Utilization of a stored heat system is possible because the engine operates on a closed cycle and simply requires a heat source--not necessarily from a combustion process. A stored heat system would probably not be practical in routine mining operations because of power and energy requirements. However, it could be used in special applications--most notably as a prime mover for a rescue vehicle. It could operate in an atmosphere not suitable for combustion (because of insufficient oxygen level) such as that occurring as a consequence of a mine fire. Also, with suitable isolation or insulation of the heat source, the likelihood of it (the engine system) acting as an ignition source would be minimal.

A version of the Stirling which utilizes a combustion system might have application in general mining operations. Because the combustion system that it utilizes is an external, continuous combustion system, the Stirling engine appears to have potential for achieving extremely low emission rates. Moreover, its theoretically attainable efficiency is greater than that of the diesel engine. However, there is a paucity of information relating to the emissions characteristics of Stirling engines based on experiments with the entire engine system although some data are available from experiments with combustors which simulate engine operation.

EXPERIMENTAL

Because of the need for more definitive data on emissions from Stirling engines, the Bartlesville (Okla.) Energy Research Center (BERC) of the Department of Energy undertook a program to obtain, via experiment, these data. The project was conducted as part of BERC's cooperative program with the Bureau of Mines for research on the reduction of pollutants from engines operated underground. An engine, leased from Philips N.V., was coupled to an electric dynamometer and operated at several speed/load points which encompassed the engine's entire operating range. Air and fuel flow rates and exhaust levels of carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NO_x), and carbon dioxide (CO₂) were measured at each engine operating condition. This information was then used to compute emission rates.

RESULTS AND DISCUSSION

A No. 2-D fuel was used in this study and the engine working fluid was helium. Initial test results showed rather high levels of CO and HC which were found to be strongly influenced by pressure (and flow) of air supplied to the fuel atomizer and to the combustion chamber. In subsequent tests, at each speed/load point, the airflow rates to the atomizer and combustion chamber were systematically varied until a minimum in exhaust CO level was observed. This operating condition was then defined as optimum. The emission levels reported here correspond to this optimized (that is, minimum CO) condition.

TABLE 1. - Performance data

Speed, rpm	Power, bhp	Airflow, lb/hr	Fuel flow, lb/hr	CO ₂ , pct	CO, ppm	HC, ppmC	NO _x , ppm
1,000	0.9	43	1.1	5.3	88	10	91
	2.5	59	1.8	6.3	147	8	104
	3.7	80	2.3	6.0	154	6	94
2,000	1.7	58	1.7	6.1	197	16	96
	4.9	87	3.0	7.1	155	10	113
	7.5	114	4.3	7.8	204	4	123
3,000	1.9	76	2.4	6.5	198	18	111
	6.4	130	4.5	7.2	170	7	97
	9.9	169	6.2	7.6	173	5	90

FIGURE 1. - Carbon Monoxide Emission Rate vs. Power Output.

FIGURE 2. - Oxides of Nitrogen Emission Rate vs. Power Output.

Results obtained in the emissions mapping experiments are given in table 1. Concentration of CO and NO_x showed little dependence on engine speed or power output; mass emissions rates of these species, however, were nearly linear with power (figures 1 and 2). Peak emission rates (table 2) for both CO and NO_x were on the order of 1.2 g/hr/rated hp. The value for NO_x is notably low in comparison with typical diesel engines which have specific emission rates of NO_x on the order of 4 to 10 (or more) grams/hr/rated hp.

TABLE 2. - Brake specific emission rates

Emission	Peak rate, g/hr/rated hp	Average rate, g/hp-hr
CO	1.3	1.6
HC	.03	.04
NO _x	1.1	1.6

Because of the low specific emission rates of CO and NO_x, ventilation requirements would be expected to be dependent only on exhaust levels of CO₂, and in fact, results of computations show this to be true (table 3). Examination of these data indicates that the "worst" case occurs at full load--approximately 600 cfm of air required to dilute the exhaust to 0.5 pct CO₂. The corresponding levels of CO and NO_x in the dilute mixture would be 10 and 5 ppm, respectively, which are well below the threshold limit values (TLV) for CO and nitric oxide (NO).

TABLE 3. - Ventilation requirements

Speed, rpm	Power, bhp	Volume for dilution to TLV's, cfm		
		CO ₂	CO	NO _x (as NO)
1,000	0.9	105	7	26
	2.5	174	26	43
	3.7	224	38	50
2,000	1.7	165	39	38
	4.9	293	42	70
	7.5	426	81	103
3,000	1.9	232	52	60
	6.4	445	72	86
	9.9	614	96	101

TABLE 4. - Peak ventilation requirements

Engine	Volume for dilution to TLV's, cfm/rated hp			
	CO ₂	CO	NO	CO + NO
Stirling	62	10	10	24
"Typical" diesel ¹	50	22	65	79

¹Approved for use in underground mines.

Computation of ventilation requirements for the Stirling engine and a typical diesel engine (approved for use in underground mines) indicates that for worst case conditions these requirements are nearly equal--approximately 65 cfm/rated hp (table 4).

However, if ventilation requirements are such that the concentration of CO divided by its TLV plus concentration of NO_x divided by its TLV is less than or equal to 1, the minimum requirement for the diesel would be increased to about 80 cfm/rated hp, which is approximately 30 pct greater than that required for the Stirling engine. Also worth noting is the fact that if the dilution is sufficient to maintain CO₂ at or less than 0.5 pct, there are no operating conditions for the Stirling engine (among the steady-state modes examined in these tests) in which the dilute mixture will contain CO or NO above its TLV.

SUMMARY AND CONCLUSIONS

Emission rates of CO, HC, and NO_x from a Stirling engine compared quite favorably with those from diesel engines. Emissions of HC were roughly 1/10 of those from "clean" diesels and NO_x was about 1/3.

The ventilation requirement, based on dilution of toxicants to allowable levels, was on the order of 60 cfm/rated hp--about the same as "typical" diesel engines. This requirement was based on CO₂, and if this air flow were supplied, the maximum CO and NO levels in the dilute mixture would be 10 and 5 ppm, respectively. These levels are far below the allowable 8-hour exposure limits.

These findings indicate superiority of the Stirling over the diesel engine in terms of emissions; however, it must be recognized that there are no Stirling engines commercially available at this time. The purpose of this study was to obtain data on emissions from an engine in order to allow a first (preliminary) assessment of the potential for use of Stirling engines in underground mines. A more complete assessment would include factors that were not addressed in this work. Some of those factors include manufacturing cost and complexity, durability of engine components, and complexity of maintenance procedures.