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AN EXPERIMENTAL INVESTIGATION OF AN EXHAUST-GAS-TO-AIR HEAT EXCHANGER FOR USE ON JET-STACK-EQUIPPED ENGINES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

As part of a general investigation of thermal ice-prevention systems, tests have been conducted of an exhaust-gas-to-air heat exchanger designed for use in aircraft incorporating individual-cylinder exhaust stacks. The thermal performance of the heat exchanger was determined as well as the effect of the heat-exchanger installation on indicated cylinder power and exhaust-jet thrust.

The results of the tests indicate that predicted steady-flow values of thermal output may be used with reasonable accuracy to design intermittent-flow exhaust-gas heat-exchanger installations, provided that unrestricted exhaust stacks are used. A reduction of approximately 3 percent of total indicated cylinder power resulted from the increased exhaust-gas-flow resistance due to the heat-exchanger installation. The loss in total head of the exhaust gas during its passage through the heat exchanger caused a reduction of exhaust-gas thrust of 15 percent at the highest jet velocity obtained. The reduction was smaller for lower jet velocities.

INTRODUCTION

During the course of a general investigation of ice-prevention techniques conducted at the Ames Aeronautical Laboratory, it was found (reference 1) that the most effective method of preventing ice formations consisted of supplying heat to the affected portions of the airplane structure. Consideration of various sources of heat revealed that the engine exhaust gas was the most obvious and practical source for the large quantities of heat required to prevent ice accretions on wings, empennage, and windshield. Use of the engine exhaust gas as a heat source, however, involved the use of exhaust-gas-to-air heat exchangers; consequently, a general research program was initiated in order to determine the performance characteristics of various types of heat exchangers suitable for installation in the exhaust systems of reciprocating aircraft engines. Considerable research (references 2, 3, and 4) has been completed in applications involving the use of a single heat exchanger located in an exhaust-gas stream of practically constant velocity such as exists with engines utilizing collector-ring-type exhaust systems. The present research is an extension of the previous work to the case of unsteady exhaust-gas flows, such as are encountered in reciprocating engines having individual-cylinder exhaust stacks, since it would be expected that the intermittent nature of the exhaust-gas flow in an individual-cylinder exhaust stack might affect the thermal performance of a heat exchanger.

It was the specific purpose of this investigation to evaluate the following factors from tests of a typical heat exchanger on a ground test stand simulating an actual engine installation:

1. The loss of cylinder power resulting from the back pressure imposed by insertion of a heat exchanger in the individual jet stack of the cylinder

2. The loss of exhaust-gas thrust resulting from the pressure drop and cooling experienced by the exhaust gas in passing through the heat exchanger

3. The effect of a pulsating gas stream on the thermal performance of the heat exchanger

All three of these factors are considered of equal importance in any practical application of heat exchangers to jet-stack-type exhaust systems.

APPARATUS AND EXPERIMENTAL METHODS

The heat exchanger tested was a flat-plate cross-flow type, as shown in figure 1, and was constructed of welded stainless-steel plates in accordance with an Ames Laboratory design. Pertinent data concerning the heat-exchanger dimensions are listed in the following table:

	Air side	Gas side
Number of passages	12	11
Passage gas, ft	0.0065	0.0092
Passage length, ft	.346	.520
No-flow length, ft	.275	.275

A schematic diagram of the heat-exchanger installation on a ground test stand is shown in figure 2. The heat exchanger was connected to the exhaust stack of cylinder 8 of a Pratt & Whitney R-985-50 aircraft engine which was rated at 450 horsepower at 5000 feet altitude. A photograph of the heat-exchanger test apparatus is shown in figure 3.

Measurements were made of the heat-exchanger thermal performance, the indicated engine cylinder power, and the exhaust jet thrust with (1) the exhaust-gas discharge from the heat exchanger unrestricted, and (2) with constricting nozzles installed downstream from the heat exchanger. The unrestricted exhaust stack had an area of 0.0193 square foot, and the two constricting nozzles tested had areas of 0.0155 and 0.0128 square foot, respectively. Each configuration was tested at three conditions of engine power and calculated exhaust-gas flow:

Condition 1.– 2200 rpm, 35 inches of mercury absolute manifold pressure, 318 pounds per hour exhaust-gas flow

Condition 2.– 1900 rpm, 30 inches of mercury absolute manifold pressure, 215 pounds per hour exhaust-gas flow

Condition 3.– 1700 rpm, 27 inches of mercury absolute manifold pressure, 163 pounds per hour exhaust-gas flow

During the tests in which the heat exchanger was in the system, the cooling air-flow rate to the exchanger was varied from about 600 pounds per hour to about 1400 pounds per hour in increments of approximately 150 pounds per hour. This was done for each engine condition. A blower was used to draw the air through the system and a valve on the blower discharge was used to control the flow. The air flow was measured by a calibrated venturi meter located in the system downstream from the exchanger.

In order to determine the effect of the heat exchanger on engine performance as well as the thermal performance of the heat exchanger, separate instrumentation was provided to measure indicated cylinder power, exhaust jet thrust, and the thermal characteristics of the exchanger. The instrumentation for each of these phases is discussed separately in the following paragraphs.

Cylinder Power Measurements

The cylinder power data were obtained from readings of cylinder instantaneous pressure made with a modified Farnboro-type instantaneous pressure recorder. The Farnboro-type recorder employs a pressure-balanced diaphragm element inserted in the system at points where data are desired – in this case directly in the cylinder. The operation of the instrument is as follows:

> The diaphragm, when activated by a pressure unbalance, triggers an electronic circuit, causing a high-tension spark to discharge from a moving stylus to a recording drum. The recording drum is driven at a definite fraction of crankshaft speed by a geared synchronous motor arrangement. The trace of the spark point on the recording paper gives the variation of cylinder pressure with crank angle.

A rotometer and a chronometric tachometer were used to measure fuel flow and engine speed, respectively. Other engine operating data were obtained with standard aircraft-type instruments.

Jet-Thrust Measurements

The jet-thrust measurements were made with a thrust tank similar to the device described in reference 5. In place of the arm and counterweight, however, a restrained deflection arm on which a strain gage was mounted was used. The strain-gage readings were a measure of bending moments in the restrained arm, which, in turn, was a measure of thrust forces on the target plate. The thrust forces measured were average thrust forces, since the exhaust pulse frequency was too high and the inertia of the apparatus was too great to measure any variation of thrust during an engine cycle.

Thermal-Performance Measurements

The thermal performance of the exchanger was determined from the increase in enthalpy of the air as it passed through the heat exchanger. The temperature of the air was measured with iron-constantan thermocouples in conjunction with a self-balancing potentiometer. The inlet-air temperature was determined with a single thermocouple located in the inlet duct, and the temperature of the air after passage through the heat exchanger was averaged with nine thermocouples connected in series and spaced across the outlet duct downstream from the heat exchanger as shown in figure 2. The exhaust-gas temperature was measured with a quadruple-shielded chromel-alumel thermocouple inserted in the exhaust manifold between cyclinders 1 and 2.

RESULTS AND DISCUSSION

The Effect of the Heat Exchanger on Indicated Cylinder Power

It was originally intended to determine changes of indicated cylinder power, due to the installation of the heat exchanger and several nozzles, by graphically integrating the instantaneous pressure records, replotted as pressure-volume diagrams. It was found, however, that the percentage change in the total indicated horsepower was small enough to be within the accuracy of the instantaneous pressure recorder so that a much better correlation of the data was obtained by using indicated pumping horsepower as obtained from the indicator diagrams; therefore, this quantity was used as a basis of comparison of the data. A comparison of the difference in pumping horsepower required for the several nozzle sizes tested, with and without the heat exchanger installed in the exhaust stack, is shown in figure 4. The data have been plotted as indicated pumping horsepower per unit nozzle area HP_p/A_n, as a function of the cylinder mass flow per revolution per unit nozzle area M_c/A_nN. The presence of the additional flow resistance offered by the heat exchanger would be expected to reduce the over-all power output by increasing the amount of pumping horsepower required to force the exhaust gases out of the cylinder. In addition to the resistance of the heat exchanger, restriction of the exhaust-gas-flow area by the nozzle offers further flow impedance. It may be seen that the installation of the heat exchanger increased the pumping horsepower over the range of nozzle sizes and engine powers tested. At the highest engine power, an approximate 30-percent increase in pumping horsepower due to the added restriction of the heat exchanger is evident. However, due to the fact that the pumping horsepower constitutes only about one-tenth of the total indicated power, a reduction of approximately 3 percent of total indicated power may be charged to the heat-exchanger installation at this maximum power condition.

The Effect of the Heat Exchanger on Jet Thrust

It has been shown in reference 5 that the thrust per unit mass flow of exhaust gas F/M_c may be correlated with the factor P_oA_n/M_c, where P_o is atmospheric pressure. The factor F/M_c may be considered as the effective velocity of the jet of exhaust gas that issues from the exhaust nozzle. The effect of the heat exchanger on the effective jet velocity is shown in figure 5. Although the data are somewhat scattered, it may be seen that the presence of the heat exchanger reduced the effective jet velocity by approximately 300 feet per second over the total range of effective jet velocities obtained. At the highest effective jet velocity obtained, 1950 feet per second, this represents a reduction in thrust of about 15 percent.

No correlation of the reduction of effective jet velocity with the amount of heat abstracted from the exhaust gas was evident. This is not surprising in view of the small temperature drop experienced by the exhaust gas in its passage through the heat exchanger.

It should be noted that the heat exchanger used in these tests was not especially designed to eliminate pressure losses. Undoubtedly, the abrupt area expansion and contraction at the entrance and exit of the heat exchanger accounted for the majority of the pressure loss. It would appear evident that a heat exchanger could be designed which would largely eliminate these losses at the expense, however, of compactness and ease of installation.

The Thermal Performance of the Heat Exchanger

The thermal performance data were corrected to standard conditions of 1700° F inlet-exhaust-gas temperature and 60° F inlet-air temperature by use of the method presented in reference 4. This reference also shows that a method, described therein, of predicting steady-flow thermal performance for this type of heat exchanger, will give results which check closely with steady-flow experimental data. The predicted steady-flow performance was used, therefore, as a basis for comparison with the intermittent-flow test data of this report, since no steady-flow experimental data were available on the test heat exchanger.

The results of the tests showing the thermal performance of the heat exchanger are presented in figures 6, 7, and 8. In figure 6 is shown the variation of thermal output Q with air-mass-flow rate for the unrestricted exhaust stack and a comparison of the data with the steady-flow thermal output as predicted by the methods presented in reference 4. It may be seen that there is fairly close agreement between the calculated steady-flow thermal output and the measured intermittent-flow thermal output for the case of an unrestricted stack. Consequently, predicted values of steady-flow thermal output may be used with reasonable accuracy for purposes of design of jet-stack heat-exchanger installations, provided that unrestricted exhaust stacks are used. The effect of nozzle restriction on thermal output is shown in figures 7 and 8 for several exhaust-gas mass-flow rates and air-mass-flow rates. It can be seen that the thermal output with restricted stacks is somewhat higher than that with the unrestricted stack. This effect is probably due to the decreased back flow of cooled exhaust gas into the heat exchanger through the exhaust stack during the exhaust-gas no-flow period. The effect may also be due to the shortening of the no-flow period due to the constrictive effect of the nozzles.

CONCLUSIONS

Engine tests have been conducted of a small flat-plate-type heat exchanger designed for installation in a jet-stack-type exhaust system where intermittent exhaust-gas flow exists. The results of the tests are listed below:

1. The predicted steady-flow values of thermal output were in sufficiently close agreement with the measured intermittent-flow thermal output to indicate that, for conditions of the present test, the use of predicted steady-flow thermal performance is satisfactory for purposes of design of jet-stack heat-exchanger installations, provided that unrestricted exhaust stacks are used.

2. The loss in total head of the exhaust gas during passage through the heat exchanger caused a reduction of thrust of approximately 15 percent at the highest jet velocity tested.

3. A reduction of approximately 3 percent of total indicated cylinder power resulted from the increased exhaust-gas-flow resistance due to the heat-exchanger installation.

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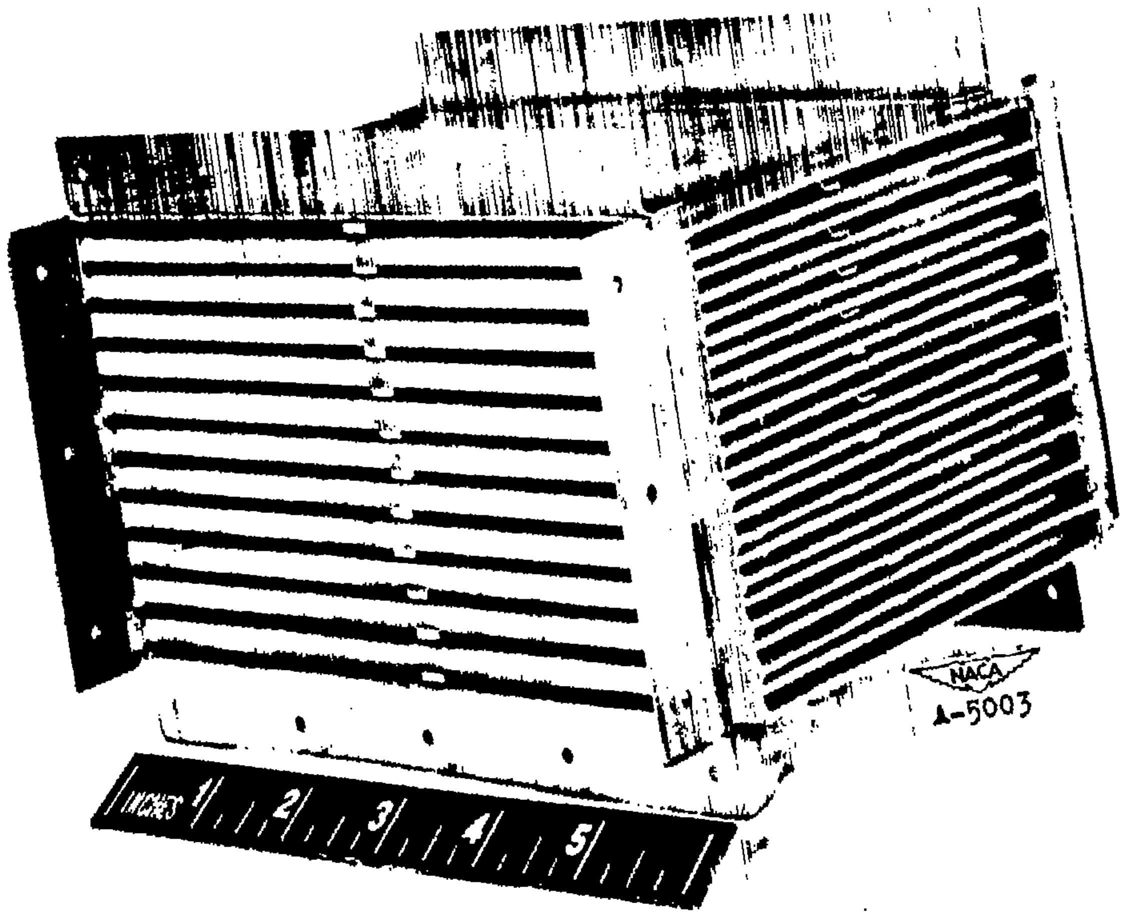

Figure 1.- Exhaust-gas to air heat exchanger used in tests.

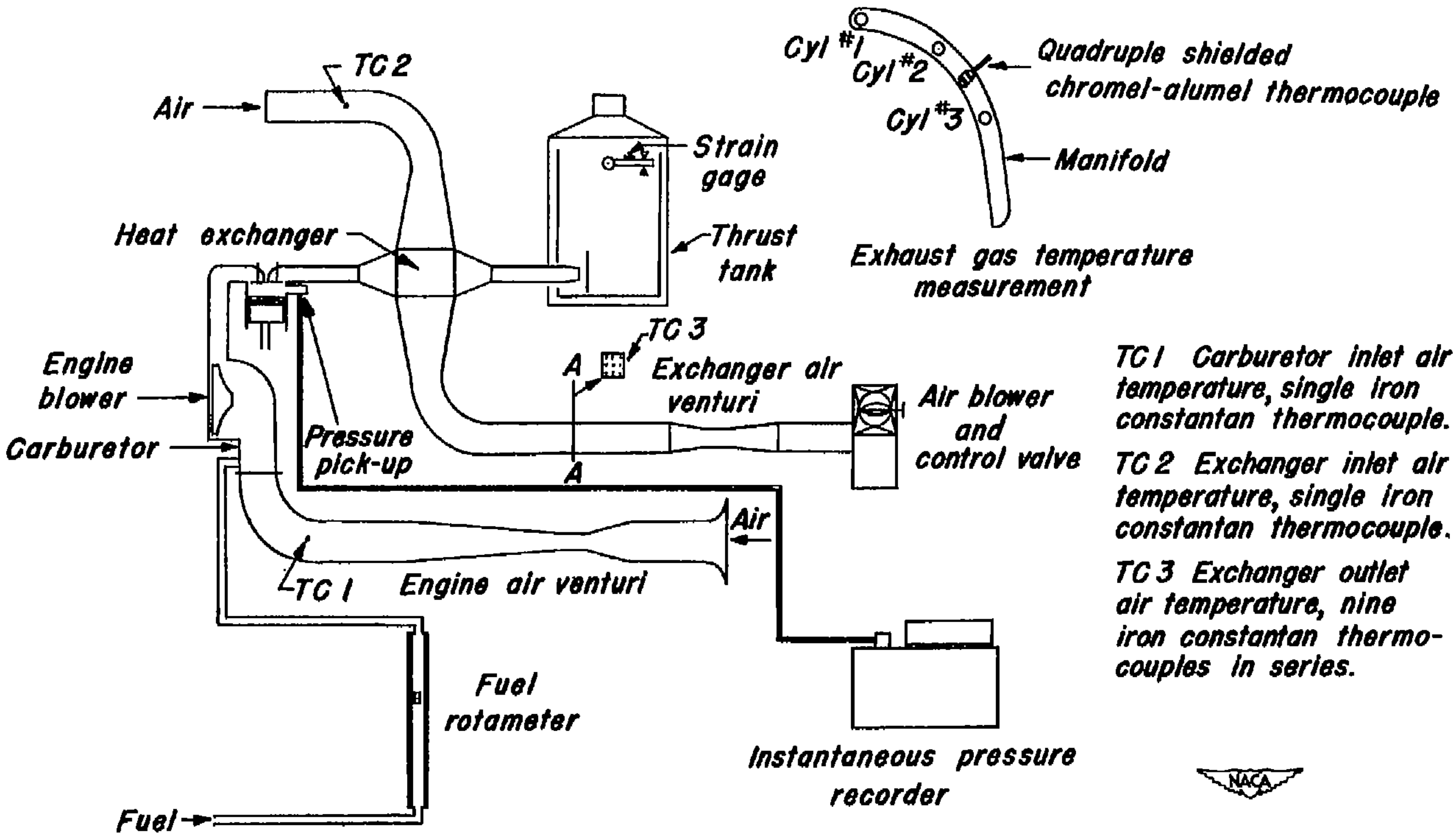

Figure 2.- Schematic diagram of heat-exchanger apparatus for pulsating flow tests.

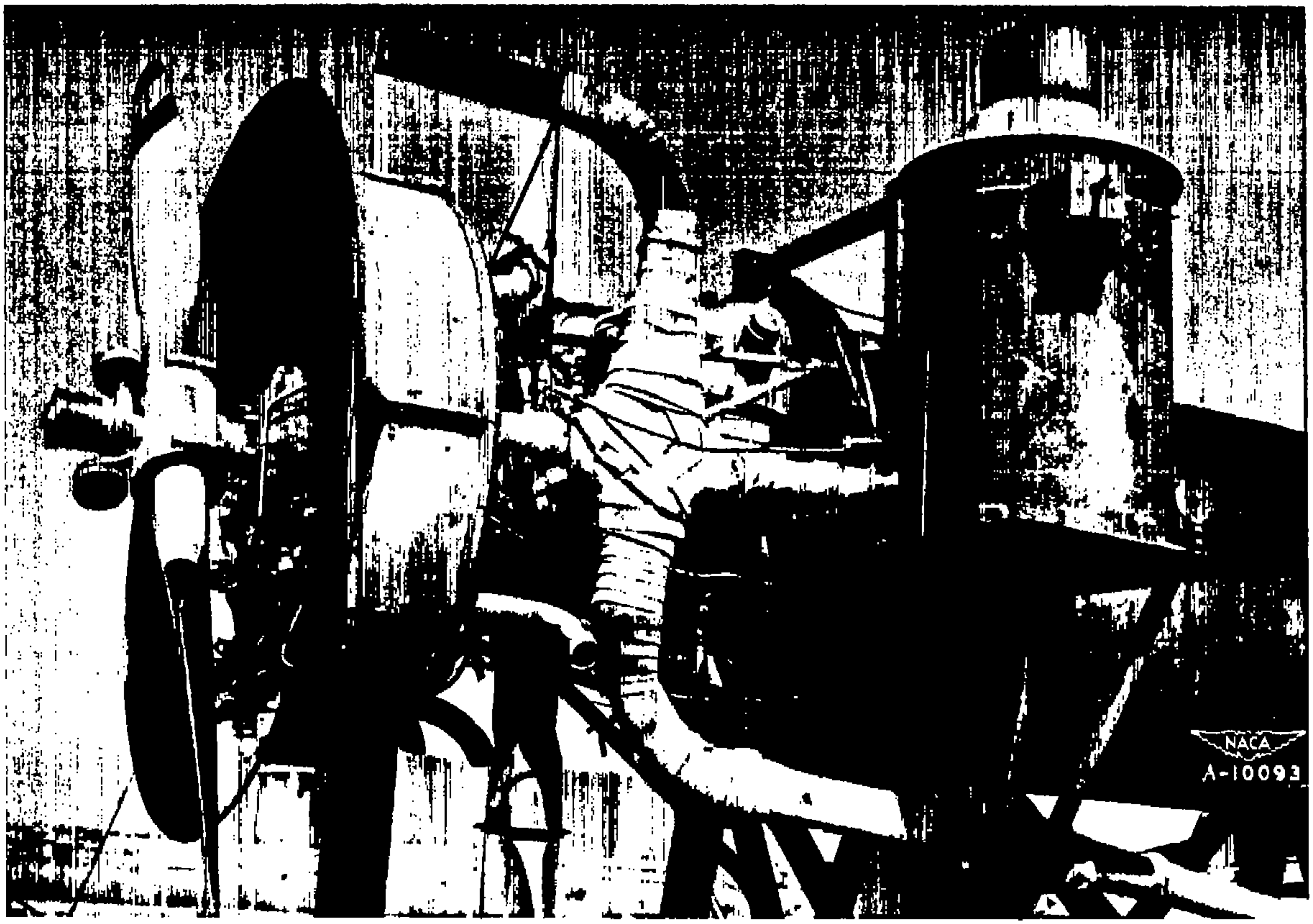

Figure 3.– Heat-exchanger and test-equipment installation on P & W R-985 engine.

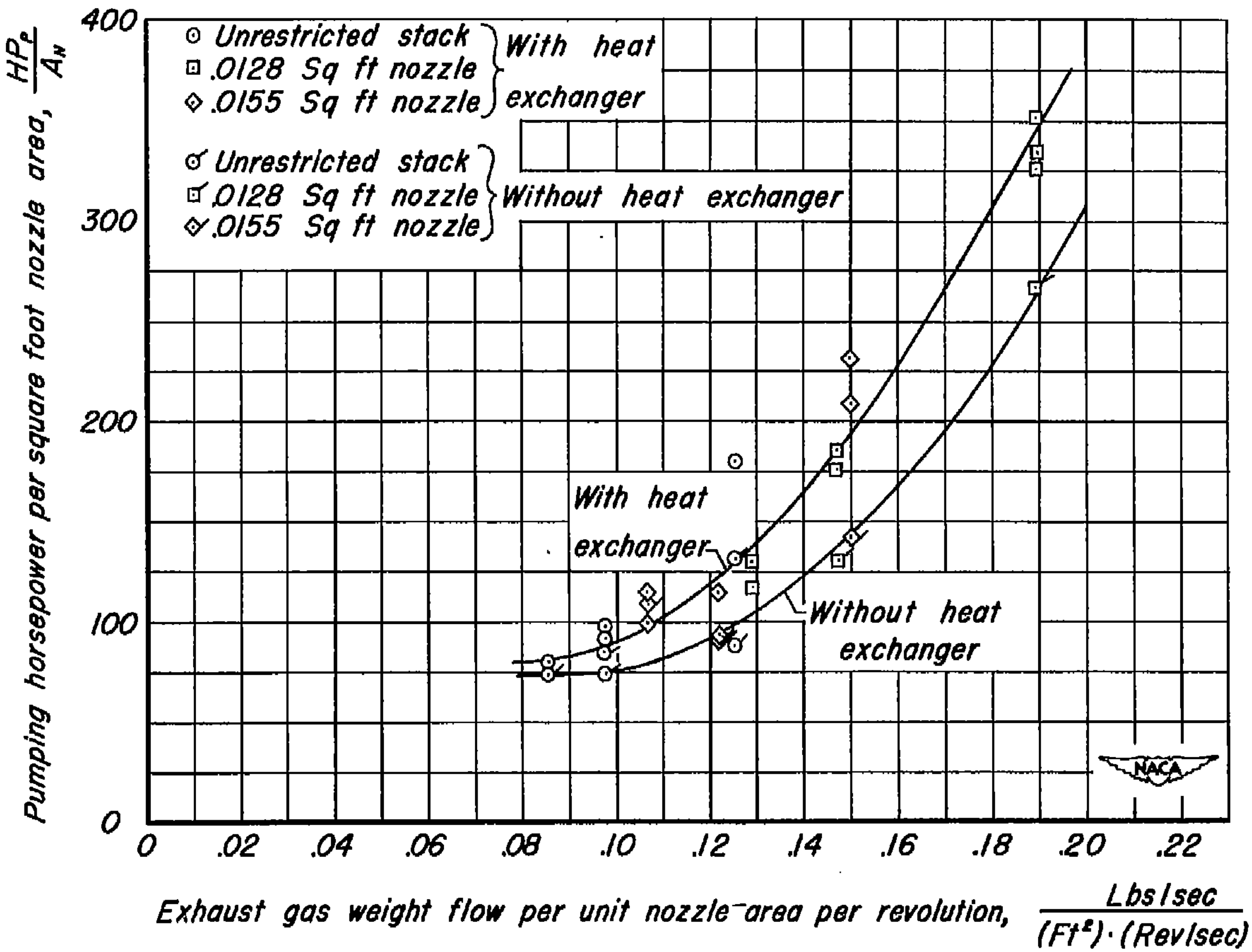

Figure 4.- Effect of heat exchanger on pumping horsepower required.

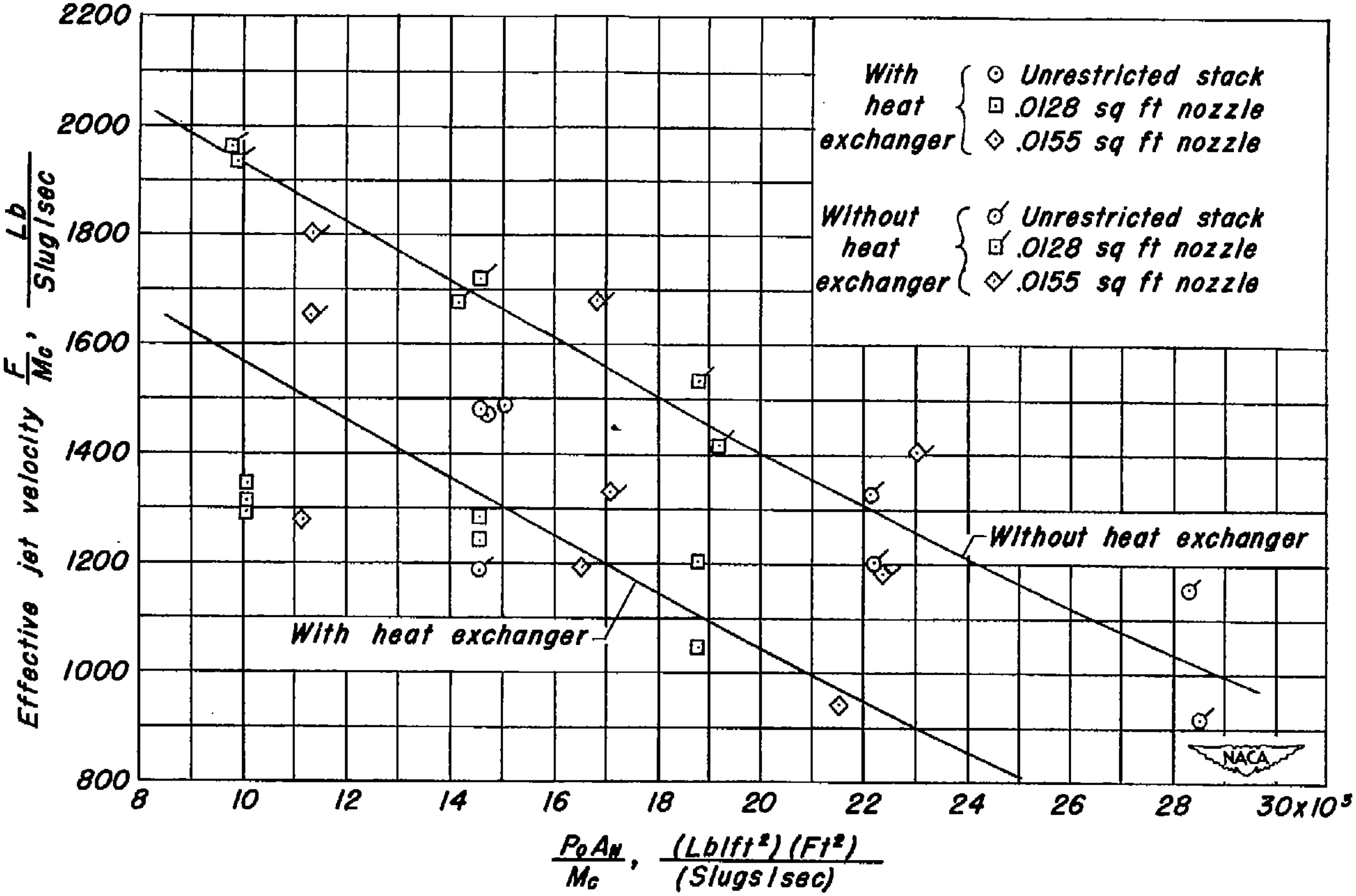

Figure 5.– The effect of the heat exchanger on jet thrust.

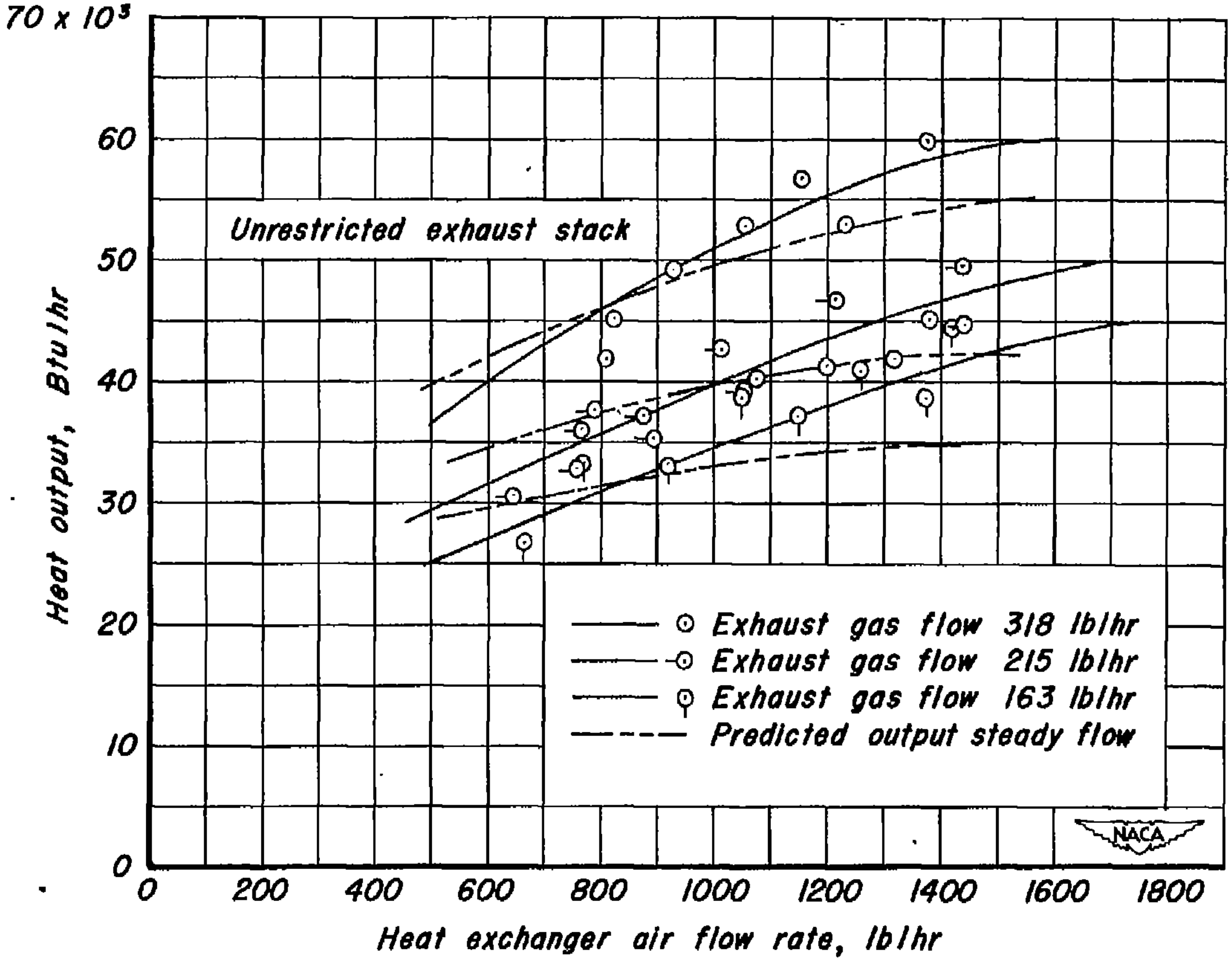

Figure 6.– Variation of heat output with heat exchanger air flow, and comparison with predicted steady flow heat output.

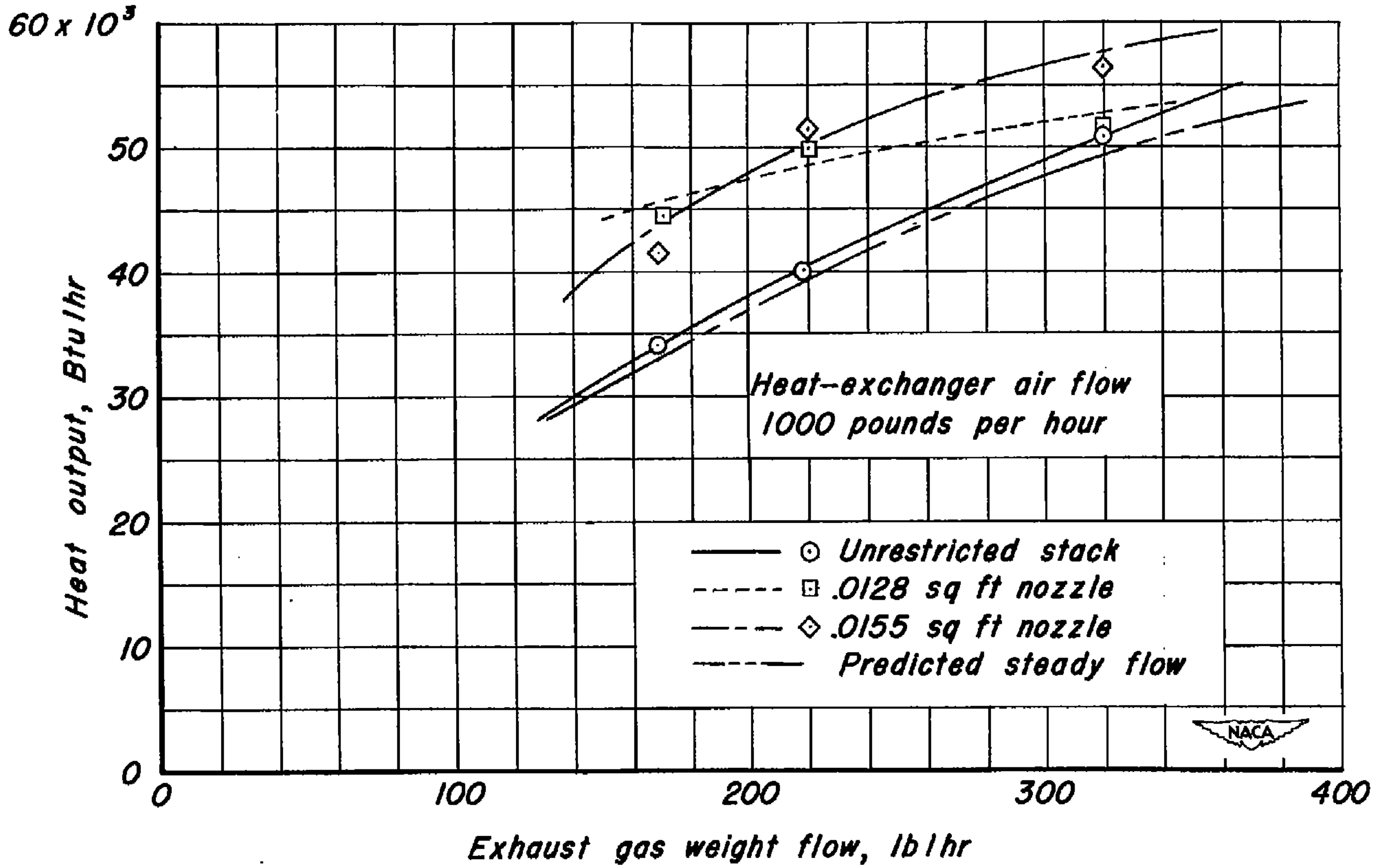

Figure 7.– Variation of heat output with exhaust gas weight flow.

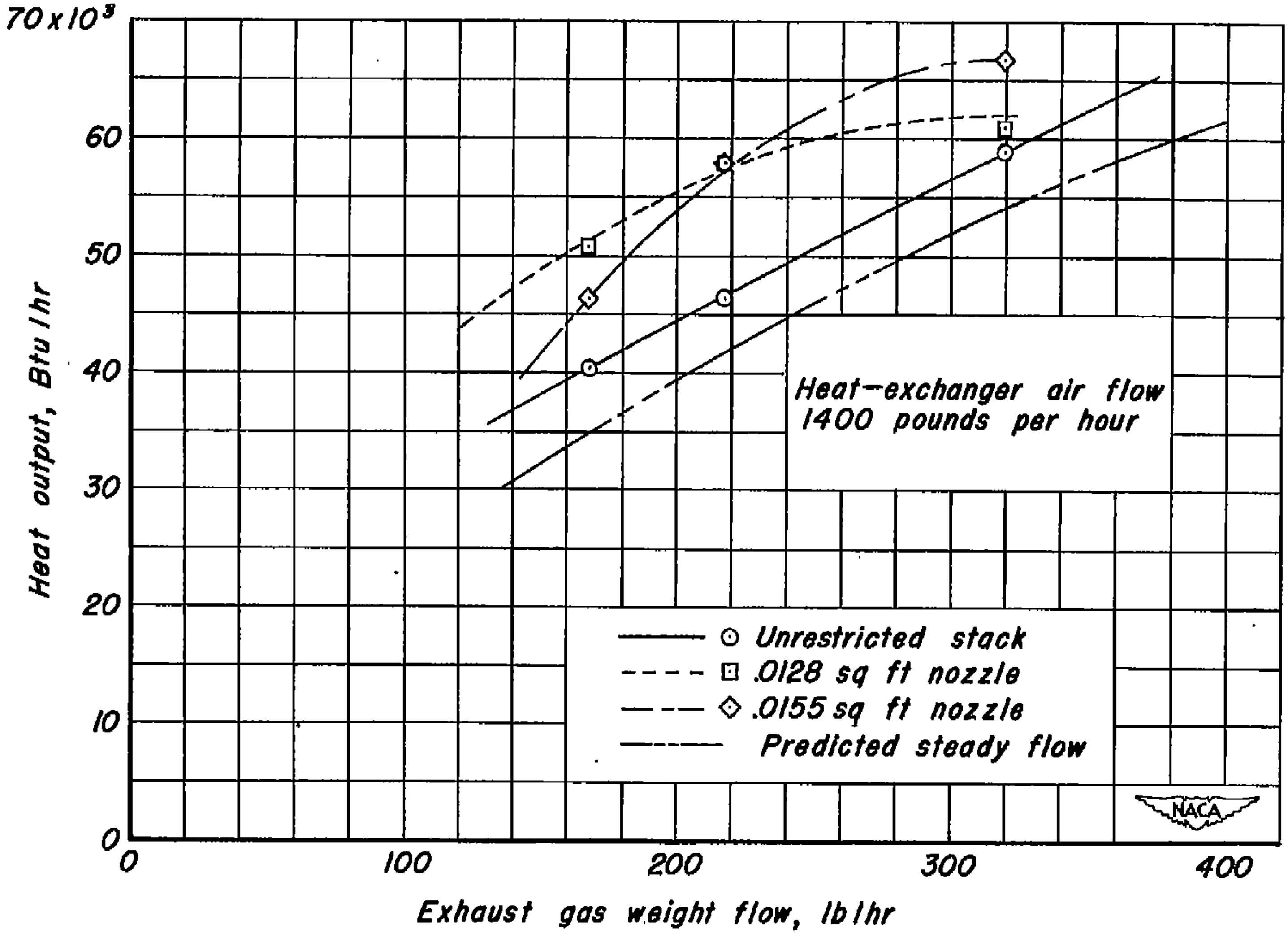

Figure 8.– Variation of heat output with exhaust gas weight flow.