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TEST RESULTS — DIRECT CONTACT HEAT EXCHANGER FOR
BIOPHASE DIESEL BOTTOMING SYSTEM

Topical Report

By
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MASTER

September 5, 1978

Work Performed Under Contract No. EY-76-C-03-1207

Biphase Energy Systems
Research-Cottrell
Santa Monica, California

U. S. DEPARTMENT OF ENERGY
DIVISION OF FOSSIL FUEL UTILIZATION

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Biphase Energy Systems

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FOR BIPHASE DIESEL BOTTOMING SYSTEM

Contract: EY-76-C-03-1207

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Prepared for the
UNITED STATES DEPARTMENT OF ENERGY

September 5, 1978

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FOREWORD

This topical report describes the effort of Task III - Contact Heat Exchanger, under Department of Energy Contract EY-76-C-03-1207. The effort was augmented by an add-on task to provide gas/liquid temperature probes in the exchanger. The effort was directed by Mr. Marvin Gunn, Program Manager, D.O.E.

ABSTRACT

A subscale, direct contact heat exchanger (one foot diameter packed column) was built and operated under conditions applicable to the Biphasic diesel bottoming cycle. Special probes for measuring gas and liquid temperatures and for measuring gas-phase compositions were designed and installed in the exchanger. The data obtained are unique in that they indicate both the extent of evaporation and condensation zones within the exchanger and the effect that those mass transport mechanisms have upon heat exchanger performance. For gas temperatures greater than 500 F it was found that the maximum temperature to which Therminol 66 could be heated was strongly dependent upon vaporization effects. Data obtained are sufficient to provide for the preliminary design of a direct contact heat exchanger using Therminol 66 as the thermal fluid. Recommendations are made for further testing using other heat transfer fluids to derive a more general engineering approach to the design of direct heat exchangers.

ACKNOWLEDGEMENT

Technical assistance is acknowledged from the D.O.E. consultants: Dr. William Thielbahr, Naval Weapons Center, China Lake, CA; Prof. Robert J. Moffat, Stanford University; and Prof. Donald M. McEligot, University of Arizona. Mr. Marvin Gunn and Mr. Michael Perlsweig of D.O.E. furnished assistance and advice.

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SECTION I

SUMMARY

The Biphase turbine cycle application to diesel engine exhaust bottoming requires heat exchange between a hot diesel exhaust and a thermal fluid. Systems have been studied which use both tubular and direct contact exchangers, but because the heat exchanger cost has a large effect on system cost the less costly direct contact exchanger has been favorably considered.¹

Data for the design of such a direct contact heat exchanger are almost totally lacking in engineering literature, especially if evaporation and condensation of the heat transfer fluid is considered. Accordingly, the Biphase diesel bottoming project included an experimental program to obtain data pertinent to the contract baseline system. The scope of this program was expanded by a later add-on to include additional data which might be used to generalize the design approach to include other fluids and other conditions.

The principal results of this test program are summarized in Table 1. The subscale contact heat exchanger was designed, built, and successfully operated to obtain the design characteristics required for the reference bottoming system in which an 1800 HP diesel engine is used. The heat transfer coefficients and actual pressure drop data were obtained for the subscale exchanger so that an initial design estimate can be made if Therminol 66 is used as the thermal fluid. It was determined that liquid Therminol 66 could be heated to a maximum temperature of 450 F when

¹U.S.E.R.D.A. SAN 1207.1, "A Biphase Turbine Bottoming Cycle for a Diesel Engine," Feb. 15, 1977.

Table 1. Contact Heat Exchanger - Test Results

1. TEST EQUIPMENT:	Experimental packed column of significant size fabricated and demonstrated - Available for further tests.
2. HEAT TRANSFER:	<p>Requirements of work statement satisfactorily completed.</p> <p>U overall data obtained.</p> <p>U less than estimated assuming no evaporation.</p> <p>Evaporation and condensation regions distinct.</p> $\frac{\text{Rate of Liquid Heating in Condensing Zone}}{\text{Rate of Liquid Heating in Evaporating Zone}} \approx \frac{4}{1}$ <p>Practical $(T_L)_{MAX} < 600 \text{ F}$ (T66 only) for $T_{gas} = 720 \text{ F}$</p>
3. SYSTEM DESIGN CONSIDERATIONS:	<p>Test results show: (1) Practical upper liquid temperature limit may be controlled by hydraulic (Δp) limitations rather than by wet-bulb temperatures. (2) Maximum liquid temperature controlled by evaporation effects.</p> <p>Operating conditions not yet optimized.</p> <p>Ageing and possible thermal degradation of Therminol 66 observed.</p> <p>Ability to predict performance of packed tower using other fluids and other conditions requires additional extended-duration runs.</p>

exposed to hot gases at temperatures up to 575°F. In the reference cycle, this temperature limitation would reduce the cycle efficiency by approximately 3 percentage points.

The phenomenon of evaporation/condensation was illuminated by the test results. Figure 1 (left side) illustrates the much smaller change in liquid temperature which results in the evaporating section compared to that in the condensing section of the packing. Similarly, Figure 1 (right side) shows the large effect on pressure drop of the evaporating fluid. These two effects, if not considered, would lead to large errors in sizing direct contact equipment if conventional design correlations were used. An understanding of these effects and development of a generalized design procedure would advance engineering knowledge in this area.

It is recommended that testing using the direct contact exchanger be continued using hot compressed air and diesel exhaust gas as heat sources. Durability runs with Therminol 66 and with other fluids of low vapor pressure are recommended. The longer runs would supply data for developing a general design correlation in the presence of evaporation/condensation. Durability running with several heat transfer fluids would supply information on the effect of diesel exhaust and water on the fluids.

INNOVATIVE RESULTS REGARDING EVAPORATION/CONDENSATION IN DIRECT CONTACT HEAT TRANSFER

SECTION II

INTRODUCTION

Tests have been conducted to obtain design data for use in sizing direct contact heat exchangers (DCHX) for the Biphasic System condition. These data are necessary for sizing the DCHX proposed for recovering the waste heat present in the exhaust of stationary diesel engines. Exhaust temperatures are of the order of 720°F and it is desired to use part of this waste energy to heat a liquid to a maximum temperature of 600°F. A portion of this thermal energy can then be converted into mechanical energy by utilizing the Biphasic turbine cycle.

The transfer of thermal energy from the hot exhaust gases to the circulating thermal fluid can be accomplished by either direct or indirect contact of the two streams. Indirect contact of the two streams, i.e., transfer of thermal energy through a separating tube wall, would enable the use of currently available design technology for design of the heat exchanger and perhaps simplify some of the design considerations. Direct contact heat transfer has been proposed, however, because a potentially smaller, more compact, and less expansive energy recovery unit results.

Data required for the design and fabrication of direct contact heat transfer devices are almost completely absent from the open literature. A limited amount of design data has been published, but most of it is for the steam-water system (see Reference 2 and 3)

²Nemunaitis, R.R. and Eckert, J.S., "Heat Transfer in Packed Towers," *Chemical Engineering Progress*, Vol. 71, No. 8, pp. 60-67, August 1975.

³Nemunaitis, R.R., Eckert, J.S., Foote, E.H., Rollison, L.R. *Heat Transfer in Packed Towers*, Norton Company, Chemical Process Products Division, Akron, Ohio, 1975.

for which the properties are considerably different from those of the thermal fluids utilized in this study. As the physical properties of the working fluid may have a profound influence on the heat transfer process, these water data are not helpful in designing a DCHX for the proposed system.

To achieve an acceptable thermal to mechanical energy conversion efficiency in the Biphase system, a liquid with a sufficiently low vapor pressure must be available. Other characteristics are also important and may be divided, generally, into the classes: ease-of-handling, costs, availability, and environmental factors. But of the characteristics desirable in the thermal fluid, a low vapor pressure is the single most important one.

Preliminary analysis of the proposed DCHX was conducted to provide a measure of anticipated performance. Two independent estimates of the expected overall heat-transfer coefficient (U) were prepared and the maximum temperature to which the proposed thermal fluid could be heated by direct contact with the exhaust gas was estimated. The latter estimate indicated that Therminol 66 could be heated to a maximum of 560°F (wet bulb temperature) when contacted with an exhaust gas at 720°F . As this was within the range of acceptable liquid temperatures for the proposed Biphase energy waste heat recovery system, and as many of the other properties of Therminol 66 were acceptable, an experimental program was initiated to obtain design data for direct contact heat exchangers utilizing this fluid.

SECTION III.
HEAT TRANSFER ANALYSIS

HEAT EXCHANGER DESIGN EQUATIONS

The heat transfer rate can be written as

$$dA = \frac{dq}{U\Delta t} \quad (1)$$

where

dA = Element of surface area required to transfer the quantity of heat dq .

ΔT = The temperature driving force for the heat transfer process.

U = Overall heat transfer coefficient.

Writing U in terms of the external area and the individual resistances

$$\frac{1}{U_o} = \frac{1}{h_o} + R_o + R_w + R_i + \frac{A_o}{h_i A_i} \quad (2)$$

where

h_o, h_i = External and internal heat transfer coefficients.

R_o, R_i, R_w = Resistance to heat transfer due to external and internal scale and due to the wall, respectively.

For a heat exchanger in which the streams flow countercurrently (see Figure 2) and for which a constant value of U can be

assumed, Equation (1) may be integrated to obtain

$$A_o = \frac{q}{U \Delta t_{lm}} \quad (3)$$

where

$$\Delta t_{lm} \equiv \frac{\Delta t_1 - \Delta t_2}{\ln(\Delta t_1 / \Delta t_2)} \quad (4)$$

Δt_1 and Δt_2 are defined on Figure 2.

For this direct contact tower (see Figure 2), the energy balance for the gas stream for an element of the column is

$$G(C_p)_G(-dT_G) = Ua(T_G - T_L)dz$$

Rearranging,

$$\int_0^Z dz = \int_{T_{G1}}^{T_{G2}} \frac{G(C_p)_G}{Ua} \frac{-dT_G}{(T_G - T_L)} \quad (5)$$

where

- G = Gas mass flow rate (lb/hr ft²)
- $(C_p)_G$ = Heat capacity of gas phase (BTU/lb °F)
- T_G = Gas phase temperature °F
- T_L = Liquid phase temperature °F
- U = Overall heat transfer coefficient (BTU/hr ft² °F)
- a = Heat transfer surface per volume of packing (ft²/ft³)
- Z = Height of tower (ft)

Equation (5) is applicable when the evaporation and condensation processes occurring within the column do not significantly affect

Figure 2. Schematic Diagram Showing Flows, Heat Duty and Element Heat Balance for Proposed Direct Contact Heat Exchanger

the direct contact heat transfer process under consideration. Although this assumption is not valid for the present case, the results obtained are useful as a reference to which experimental data may be compared. G , $(C_p)_G$ and U would then remain substantially constant so that

$$Z = H_{OG} \cdot N_{OG} \quad (6)$$

where

$$H_{OG} = \frac{G(C_p)_G}{Ua} = \text{height of transfer unit;} \quad (7)$$

$$N_{OG} = \int \frac{-dT_G}{(T_G - T_L)} = \text{number of transfer units}$$

We may also write from Eqs. (6) and (7):

$$N_{OG} = \frac{Z}{H_{OG}} = \frac{U(Za)}{G(C_p)_G} = \frac{US}{\dot{m}(C_p)_G} = \text{NTU}$$

where S is the total heat transfer surface, $\dot{m}$ is the total gas rate (lb/hr), and NTU is the number of transfer units as often referred to in heat exchanger analysis⁴.

For the above conditions the calculated column temperature profiles become linear (see Figure 3), and for the particular case under consideration the linear profile indicates that 8.4 transfer units will be required. The total column height can then be calculated once H_{OG} , the height of the transfer unit, is known.

⁴Kays, W.M., and London, A.L., *Compact Heat Exchangers*, McGraw-Hill, 1958.

Figure 3. Calculation of Number of Transfer Units by Neglecting Effect of Evaporation and Condensation on Temperature Profile

HEAT TRANSFER COEFFICIENTS

Design correlations to supply H_{OG} or U for direct contact heat exchangers, generally, are not available in the literature. However, the magnitude of the individual interphase heat transfer coefficients (h_L , h_G) can be estimated using heat/mass transfer analogies. U , the overall interphase heat transfer coefficient, can then be obtained from

$$\frac{1}{U} = \frac{1}{h_L} + \frac{1}{h_G}$$

where R_o , R_i , and R_w become zero and A_o/A_i is unity (see Equation 2).

Because the flow regimes in direct contacting equipment normally are highly turbulent and ill-defined, theoretical analysis of the transport processes is not helpful in predicting interphase transfer coefficients directly. It is of use only as an aid in correlating experimental data. Interphase transport data available for direct contacting gas-liquid devices have been obtained, almost exclusively, for mass transfer operations, and they are generally presented in the form of overall mass transfer coefficients (K_G or K_L) or as height of transfer units (H_{OG}) (see, e.g., References 5 and 6). In some specialized cases it is possible to deduce individual phase coefficients (k_G and k_L) from overall coefficients. If the latter is possible the heat/mass transfer analogy may be used to deduce individual heat transfer coefficients (h_G and h_L) so that an overall heat transfer coefficient U can be obtained. Thus, the phenomenological relation for mass transfer is⁶

$$\dot{m}'' = K_G A (p_G - p_L)$$

⁵*Chemical Engineer's Handbook*, McGraw-Hill, 5th Edition, 1973.

⁶Treybal, R.E., *Mass Transfer Operations*, McGraw-Hill, 2nd Edition, 1968.

where

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{m}{k_L}$$

and m is the Henry's law constant for the solute in the liquid phase. For heat transfer

$$\dot{q}'' = UA(t_G - t_L)$$

Values of h_G , h_L and U , assuming negligible vaporization of the thermal fluid, were calculated previously¹ using a correlation for mass transfer coefficients derived by Onda, et al⁷.

$$k_L \left[\frac{\rho_L}{\mu_L g} \right] = 0.0051 \left[\frac{L}{a_w \mu_L} \right]^{\frac{2}{3}} \left[\frac{\mu_L}{L D_L} \right]^{-0.5} (a_t D_\rho)^{0.4} \quad (8)$$

$$\frac{k_G RT}{a_t D_G} = 5.25 \left[\frac{G}{a_t \mu_G} \right]^{0.7} \left[\frac{\mu_G}{\rho_G D_G} \right]^{\frac{1}{3}} (a_t D_\rho)^{-2.0} \quad (9)$$

where the wetted packing surface (a_w) can be calculated from

$$\frac{a_w}{a_t} = 1 - \exp \left[-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} Re^{0.1} Fr^{-0.05} We^{0.2} \right] \quad (10)$$

the above expressions are dimensionally consistent where

k_L, k_G = Liquid and gas phase mass transfer coefficients

ρ_L, ρ_G = Liquid and gas phase densities

⁷Onda, K., Takeuchi, H., and Okumoto, Y., "Mass Transfer Coefficients Between Gas and Liquid Phases in Packed Columns," *J. Chem. Eng.*, Japan, 1, 1968 (56).

- μ_L, μ_G = Liquid and gas phase viscosities
- L, G = Liquid and gas phase superficial mass flow rates
- D_L, D_G = Liquid and gas phase diffusivities
- a_u, a_t = Wetted and total surface area of packing
- D_p = Nominal packing size
- g = Gravitational constant
- σ_c = Critical surface tension of packing material
- σ = Surface tension of liquid
- Re = Reynolds number ($G/a_t \mu_G$ or $L/a_t \mu_L$)
- We = Weber number ($L^2 / \rho_L \sigma a_t$)
- Fr = Froude number ($a_t L^2 / g \rho_L^2$)

Once the mass transfer coefficients (k_L and k_G) have been obtained using equations (8), (9) and (10), h_L and h_G can then be found from:

$$h_G = k_G P_{BM} C_p \left[\frac{Sc}{Pr} \right]^{0.67}$$

$$h_L = k_L C_p \left[\frac{Sc}{Pr} \right]^{0.67}$$

where P_{BM} is the logarithmic mean partial pressure of the non-diffusing component. Results of calculations using the above equations for 2" pall rings in the system of interest are shown in Table 2.

Calculations to estimate the gas phase convective heat transfer (h_G) coefficients were also prepared by McEligot.⁸ As total resistance to heat transfer is composed mainly of the gas phase

⁸McEligot, D.M., Personal Communication, February, 1978.

Table 2. Estimates of h_L , h_G and U for 2" Pall Rings at
a Pressure Drop 0.8 inches H_2O /ft of Packed Bed

Temp °F	G lb/hr-ft ²	L a_w lb/hr-ft ²	ft ² /ft ³	k_G moles/hr-ft ² -atm	k_L $\frac{lb_{moles}}{hr-ft^2-lb_{moles}/ft^3}$	h_G B/hr-ft ² -°F	h_L B/hr-ft ² -°F	$\frac{1}{U} = \frac{1}{h_G} + \frac{1}{h_L}$	U
200	1625	641	23.25	0.16	0.06724	12.364	63.87	0.0965	10.36
400	1625	641	23.25	0.1631742	0.71359	14.144	183.67	0.0761	13.133
550	1625	641	23.25	0.16053	2.06493	14.257	293.686	0.0735	13.70
700	1625	641	23.25	0.20709	4.141	14.213	426.85	0.0727	13.76

resistance (see Table 2), the gas phase coefficients by themselves provide a good first estimate of what the overall coefficient (U) will be. The range of column conditions that McEligot considered was not specified; however, he included results from correlations due to several other investigators. These results are summarized in Table 3.

Moffat⁹ estimated the effects that evaporation and condensation would have on the gas phase heat transfer coefficient. He showed that local gas-phase coefficients (h_G) within the

Table 3. Estimated Gas Phase Coefficients (h_G)
Using 2" Intalox Saddles as Column Packing⁸

Experimental Basis of Correlation	Predicted h_G (Btu/hr-ft ² -°F)
Particle-to-gas heat transfer, mostly spheres. ¹⁰	9.1
Evaporation of water from porous packing elements. ¹¹	18.5
Sublimation from solid naphthalene. ¹²	12.5
Gas absorption in liquids and vaporization of flowing water, accounting for wetted area. ⁷	9.5

⁹Moffat, R.F., Personal Communication, February, 1978.

¹⁰Gupta, Chaube, and Upadhyay, *Chem. Eng. Sci.*, 1976.

¹¹Taeker and Hougen, *Chem. Engr. Prog.*, 44, 529 (1948).

¹²Shulman and Margolis, *AICHE J.*, 3, 157 (1957).

liquid-gas contactor would deviate substantially from those estimated assuming that no evaporation or condensation took place. At the bottom of the column, where evaporation occurs and interphase mass and heat transfer are directionally opposed (see Figure 4), the heat transfer coefficient, h_G , was shown to be reduced by a factor of 4.-5. Likewise, a large improvement in the coefficient would be expected in the upper part of the column where condensing vapors would augment sensible heat transfer. Moffat also estimated that the maximum temperature to which Therminol 66 could be heated when exposed to exhaust gases at 720°F would be ~560°F. This corresponded to the calculated wet bulb temperature of the Therminol.

Figure 4. Evaporation/Condensation Processes for Direct Contact Heat Transfer in a Packed Column

SECTION IV

EQUIPMENT AND INSTRUMENTATION

The direct contact heat exchanger was sized to permit the experimental verification of the packing depth required to heat the thermal fluid to the desired temperature (500°F) by direct contact with a diesel exhaust stream. The cross-sectional area of the exchanger was ~1/5 of that estimated as being necessary for the 1800 HP diesel engine reference system defined in Reference 1. The resulting experimental equipment was considerably larger than laboratory equipment so that wall effects would be minimized and commercial sized packing could be used. The exchanger selected was compatible with a Biphasic cycle which utilized the exhaust from a diesel engine in the 200-300 HP range, which is most likely for continued demonstration programs.

TEST EQUIPMENT

The test equipment is shown in the schematic, Figure 5. The contact heat exchanger consists of a 1-foot diameter packed bed of variable height. It has provisions below for the entry of hot gas and the exit of hot liquid, and provisions above to inject cold liquid and for cool gas exit. The liquid circuit, designed for a heat transfer fluid such as Therminol 66 (Monsanto Co.), includes a distributor tray above the packing, and a section below the packing where hot liquid passes through a water-cooled heat exchanger, and is pumped (via a filter) to the top of the exchanger to complete the circuit.

The packing of the heat exchanger was 1-inch Pall Rings made of carbon steel. The exchanger body (Figure 6) was fabricated from a section of 12-inch pipe. Standard flanges were used at the top and bottom and in the center as a support. Commercial parts

Max. Gas Rate: 0.3 lb./sec.
 Max. Liquid Rate: 0.2 lb./sec.
 Max. Gas Temp. In: 700 F

Figure 5. Direct Contact Heat Exchanger Test Equipment

30				
29				
28				
27	2	PIPE COUPLING	CARB STEEL	1 1/2" PIPE
26	2	1 1/2" GATE VALVE	BRONZE	STD.
25	4	SIGHT WINDOW	CARB ST/PYREX	1/2" SEE 1/2" SIGHT WINDOW SCREEN HARDEN
24				
23				
22		JACKETING - INSULY		
21		INSULATION		
20	1	PIPE ASSY		
19	1	CONNECTOR	CRES 316	3" MALE SWAGelok
18	2	CONNECTOR	CRES 316	3" FEMALE SWAGelok
17	1	ELBOW-FLANGED LONG	C.I.	2" PIPE DUCOMMUN METAL CO
16	1	LIQUID LEVEL GAGE	CRES.	1/2" CRES. 3/4" PIPE DUCOMMUN METAL CO
15	12	SEAL	CRES	1/2" THORPE INSULY CO
14	12	RETAINING BAND	CRES	1/2" STRIP THORPE INSULY CO
13		JACKETING - INSULY	ALUMINUM	1/4" THK THERMO 12
12		INSULATION	CALCIUM SILICATE	1/2" THK THERMO 12
11	7	PACKING	CARBON STEEL	PALL RINGS - 1" DIA. MORTON CHEM. PROCESS
10	1	DEMISTER	BE - 261	FLEXIMESH 1/2" CRES. PROCESS 600T. SO.
9	1	DISTRIBUTOR	BE - 260	MODEL B45. CRES. MORTON CHEM. PROCESS
8	1	SUPPORT PLATE	BE - 259	MODEL B18. CRES.
7	1	BASKET - 8" PIPE		STD. ASBESTOS DUCOMMUN METAL CO
6	1	GASKET - CAP		STD. ASBESTOS
5	4	GASKET - LIQ. FEED PIPE		STD. ASBESTOS
4	1	PIPE - LIQUID FEED	BE - 265	
3	3	RING - SUPPORT ASSY	BE - 264	
2	1	CAP ASSY	BE - 263	
1	1	CYLINDER ASSY	BE - 262	

Item No.	Qty	Description	Material / Dwg No.	Specification or Source
BE - 258	1	ASSEMBLY - CONTACT HEAT EXCHANGER	NOTED	Biphas Engines Inc. Santa Monica, California
BE - 259	1	SUPPORT PLATE	NOTED	
BE - 260	1	DISTRIBUTOR	NOTED	
BE - 261	1	DEMISTER	NOTED	
BE - 262	1	CYLINDER ASSY	NOTED	
BE - 263	1	CAP ASSY	NOTED	
BE - 264	3	RING - SUPPORT ASSY	NOTED	
BE - 265	1	PIPE - LIQUID FEED	NOTED	
BE - 266	4	GASKET - LIQ. FEED PIPE	NOTED	
BE - 267	1	GASKET - CAP	NOTED	
BE - 268	1	BASKET - 8" PIPE	NOTED	
BE - 269	1	SUPPORT PLATE	NOTED	
BE - 270	1	DISTRIBUTOR	NOTED	
BE - 271	1	DEMISTER	NOTED	
BE - 272	7	PACKING	NOTED	
BE - 273	12	SEAL	NOTED	
BE - 274	1	LIQUID LEVEL GAGE	NOTED	
BE - 275	1	ELBOW-FLANGED LONG	NOTED	
BE - 276	2	CONNECTOR	NOTED	
BE - 277	1	CONNECTOR	NOTED	
BE - 278	1	PIPE ASSY	NOTED	
BE - 279	1	INSULATION	NOTED	
BE - 280	1	JACKETING - INSULY	NOTED	
BE - 281	4	SIGHT WINDOW	NOTED	
BE - 282	2	1 1/2" GATE VALVE	NOTED	
BE - 283	2	PIPE COUPLING	NOTED	

Figure 6. Contact Heat Exchanger Assembly

included a packing support, liquid distribution tray, and demister. View ports were provided just below the bed and above the distribution tray. The design included provision for experimental measurement of temperature, pressure, pressure distribution, and gas composition. The heat exchanger is shown during erection in Figure 7 and after installation in the Frontispiece. In these photographs, the access platforms are apparent.

The gas furnace (background, Figure 7) has high pressure tubes and headers and is rated at 870,000 BTU/hour. The test cooler is shell and tube, with water in the shell. The centrifugal pump is rated at 2 GPM, and the filter has a pore diameter of 20 microns.

Compressed nitrogen was selected as the test gas (substitute for diesel exhaust in the ultimate application) because of the convenience it provided in controlling gas pressures and flows, because of the consistent physical properties it provided, and because of the ease of heating it in the furnace. The heat transfer fluids to be evaluated were flammable, and although auto-ignition temperatures were high, it was desired to avoid a potential fire hazard during initial testing by using the inert gas. The test program consumed approximately 120,000 SCF of nitrogen.

The nitrogen was supplied from a tube trailer, heated inside tubes in a gas fired furnace, and injected into the exchanger below the packed bed. The cooled gas exited to the atmosphere at the top of the exchanger after passing through a demisting pad. Ancillary equipment included a cooling tower for the heat exchanger water and a steam boiler used for preheating the thermal fluid.

The equipment was assembled so that the nitrogen injection subsystem could be replaced at a later time with the exhaust from a 250 HP diesel engine for tests of different fluids and for endurance testing.

Figure 7. Direct Contact Heat Exchanger, Installation

Therminol 66 (Monsanto Co.) was selected as the heat transfer fluid in accordance with its selection for the baseline diesel bottoming system (Reference 1).

INSTRUMENTATION

Instrumentation was provided consistent with the R&D role of the equipment. Figure 8 shows locations of temperature, pressure, and flow instruments. Temperatures were measured by type K thermocouples, except for several direct reading thermometers (not shown) used to adjust heat exchanger flows. The control instruments for the gas furnace are not shown in Figure 8. Pressure gages used conventional Bourdon tubes. Pressure drops were read by both vane type (Magnehelic) and damped type gages. Gas flow was metered by an orifice meter which had been calibrated with a large rotameter. In the later runs these two instruments were used in series. Liquid flow rates were determined by measurements from an orifice meter calibrated with Therminol 66 at operating temperatures. Temperatures in the packed bed were determined with the thermocouple/sampling probes described below.

TEMPERATURE PROBES, GAS/LIQUID

As the nature of the experiments became defined, it was determined that temperature data at various locations within the packed bed would be desirable. These data would help interpret the phenomenon of evaporation in the lower section of the bed and recondensation in the upper section. As the temperature of the ascending gas is higher than that of the descending liquid (at any location in the bed), it was desirable to be able to discriminate between them.

The approach to this measurement problem was to provide sensing probes with sampling holes in the top to receive descending liquid, and in the bottom to collect gas. The design, shown in

Figures 9 and 10, incorporates several features suggested by Moffat⁹. Figure 10, a section of the probe, shows the fixed tube which extends across the 12-inch diameter of the column and which has sampling holes in the top for liquid and in the bottom for gas. The movable probe fits inside the fixed tube, and has one hole which may be indexed with either a liquid or a gas sampling hole. When so indexed, the fluid or gas flows through the sampling hole and past a thermocouple in the probe annulus to the outside of the column. The sample flow is maintained either by the column pressure or by an external vacuum pump.

The fixed tube of the probe is provided with side plates to assist in collecting liquid for sampling on top, and to guide the liquid flow around the probe so that gas may be sampled from the bottom sampling hole. Gas or liquid sampling is selected by the appropriate positioning of the control lever for the movable probe.

The detailed design of the side plates, sizes of holes, and other parts of the probe geometry was assisted by subscale experiments in a transparent 6-inch column using an air-water system (Figure 11). Several design iterations were tested, resulting in the probe geometry defined in Figures 9 and 10 which differentiated between gas and liquid temperatures under mass flow rates comparable to those existing in the larger apparatus. Six liquid/gas probes of this design were fabricated and installed in the experimental column at the bed locations shown in Figure 12.

Figure 8. Instrumentation, Direct Contact Heat Exchanger Test

10	1	REDUCER	SS-200-R-4	SWAGelok REDUCER, 1/2 TUBE x 1/8 TUBE
9	1	WASHER - FLAT	ST.	STD WASHER - 3/8 IF REQD
8	1	UNION TEE	S-400-3	SWAGelok UNION TEE, 1/2 TUBE x 3/8
7	1	THERMOCOUPLE	K-18E-304-SST-1/8-18-OK	CHROMEL-ALUMEL - 1/8 CRES SHEATH-EXPOSED, 1/8
6	1	WASHER - LOCK	ST.	STD. SPRING LOCK WASHER, (.094 THK)
5	1	SHOULDER SCREW	STANDARD	3/8 DIA x 2 1/2 SHANK - 5/16 x 18 THD. REF: ALLEN
4	1	PROBE LATCH	BE-274	
3	1	GASKET	BE-275	
2	1	PROBE ASSY	BE-267	
1	1	OUTER TUBE ASSY	BE-268	

Next Assy: BE-	No. Req'd: 6	MATERIAL	Biphas Engines Inc. Santa Monica California
Final Assy: BE- 258		SPECIFICATION	
UNLESS OTHERWISE SPECIFIED All dimensions are in inches and apply after chemical treatment and/or plating All machined fillets .010 - .020 R Break all sharp edges .005 - .015 R TOLERANCES .XX ± .030 Angles ± .XXX ± .010			
CONTRACT NO 101 FINISH ON 2. COOKE 3-3-79 SIZE D BE-273 SCALE FULL SIZE WT 1.4 #MESH / OF 1			
DO NOT SCALE DRAWING			

Figure 9. Gas/Liquid Temperature Probe

Figure 10. Section of Gas/Liquid Temperature Probe

Figure 11. Six-Inch Packed Column for Development of Gas-or-Liquid Temperature Probe

Figure 12. Diagram of Packed Column Instrumentation, 96-Inch Bed

SECTION V

EXPERIMENTAL PROCEDURES

Data presented in Section VI of this report show that the heat exchanger system required ~25 minutes of operation to approach a steady state. Because of limitations in run length occasioned by use of stored nitrogen, one test objective was to minimize the time required for temperature stabilization of the column. Accordingly, a preheat cycle was adopted in which steam was supplied to the shell side of the water cooler as the Therminol 66 was circulated through the system. The packed bed and piping were preheated to approximately 250 F by this means.

A series of shakedown runs was made to assure proper operation of the various pieces of test equipment, to gain experience in control of the apparatus and to adjust and calibrate the various measurement devices. Liquid only runs were made for calibration and for pre-test column heat-up.

HEAT TRANSFER FLUID

Therminol 66 was used for all tests reported herein. Total operating time was over 8 hours. The fluid was exposed to air at the top of the column, but only at low temperatures. The Therminol was inadvertently exposed to water from a companion program which used the gas furnace on several occasions. This small amount of contamination was tolerated for these tests because Therminol and water were contacted naturally as part of the Biphase turbine cycle. In these tests, however, it was found that the Therminol and water formed an emulsion type mixture from which the two components were not easily recovered. The resulting fluid cavi- tated readily in the pumps and had to be heated to above 300 F at atmospheric pressure to separate the components.

It was also found that if the Therminol 66 were heated to 440 F or more in the exchanger a fine vapor cloud was emitted from the top of the tower. Chemical analysis showed this cloud to be condensed Therminol 66 vapor. The latter observation indicated a future concern with adequacy of the demister section at the top of the tower to prevent loss of the fluid.

Unused, liquid Therminol 66 has a transparent light yellow color. After several heating cycles, however, the fluid became opaque and dark in color, and a small amount of black sludge was deposited in the water-cooled heat exchanger. Samples of the new and used Therminol were returned to the manufacturer for analysis and comment.

GAS/LIQUID TEMPERATURE PROBE

The measurement probes described in the preceding section operated as designed in measuring liquid temperature. The packed bed pressure was sufficient to initiate liquid flow in the probe annulus when the sampling hole was turned up to receive liquid. Consistent results were not obtained, however, from the "hole down" setting for gas temperature measurement. Apparently, the liquid flow conditions were such that liquid drops or aerosol entered the probe along with the gas. Even though the gas was at a higher temperature than the liquid, the thermocouple reading approximated the liquid temperature. This was in contrast to the results of preliminary tests performed with a water/air system (see Section IV), in which good separation of air and water was obtained depending on probe setting.

The gas temperature measurement was further investigated as follows. Air was blown into the probe (reversed flow direction) with the column operating. The indicated temperature dropped promptly to the air temperature. The air flow was then interrupted and column gas was permitted to flow out of the probe as

the temperature indication increased to approximately the liquid temperature. At this point, the gas flow which had been clear of liquid began to include slugs of liquid, and the temperature did not further increase toward gas temperature. This behavior was consistent; however, the test time available was not sufficient to check-out and evaluate the ultimate potential of these probes for discriminating between liquid and gas temperatures. This evaluation awaits future tower operating programs with air or diesel engine exhausts when extended periods of operation will be available for experimentation with the probes. Although the probes were designed so that either liquid or gas samples could be extracted from the column for analysis, this operation was not attempted in the present program.

SECTION VI

EXPERIMENTAL RESULTS AND DISCUSSION

Data from which the experimental results were derived are presented in Tables A1, A2 and A3 in the Appendix for Tests 1 to 4. Measured gas and liquid flow rates and calculated heat duties and temperature differences for the gas and liquid phases are presented as a function of time. Column temperature profiles for each test are shown below in the figures accompanying the discussion of each test. Important experimental variables are identified in Table 4.

TEST 2

The location of instrumentation utilized in the column is indicated in Figure 12. A temperature history of the column for Test 2 is shown in Figure 13. After preheating the column to $\sim 350^{\circ}\text{F}$ (T_w = column wall temperature) by circulating hot liquid, the column was maintained in a heated condition until the start of the test at time 2:05. The test was initiated with a gas inlet temperature of 635°F which was reduced to $\sim 525^{\circ}\text{F}$ in the latter stages of the test. The gas outlet temperature increased steadily throughout the test.

Although a steady-state was never achieved, technically, for this test (unstable gas outlet temperature), an effective steady-state within the limitations of the experimental measurements, and for purposes of a heat balance may be claimed. Liquid inlet and outlet temperatures were stable at $\sim 110^{\circ}\text{F}$ and 430°F , respectively, and the column temperature profile was steady over a period of several minutes. As the gas residence time within the column was short (~ 2 seconds), small gas-phase temperature variations over a period of several minutes would not disrupt a heat

Table 4. Test Conditions for Direct Contact Heat Exchanger Data Runs

Test No.	Run Date 1973	Clock Time for Following Data	Run Duration (Min)	Liquid Flow GPM	Gas Flow GPM	Temp. Gas In F	Temp. Liquid Out F	
				1.18	239			Nominal
A	6-2	---	60					Shakedown and Warmup Runs ↑ ↓
B	6-6	---	60					
C	6-8	1510	65	---	101	301	---	
D	6-10	1055		1.71	146	355	225	
		1140	70	1.27	147	455	254	
E	6-13	1455		1.18	143	465	252	
		1515		1.76	143	475	230	
		1550	80	1.53	187	465	255	Shakedown and Warmup Runs
F	7-7	1435	35	1.09	69	485	270	
1	7-7	1530	50	1.27	191	575	425	Data Runs ↑ ↓ Data Runs
2	7-13	1422	25	0.84	206	530	433	
3	7-24	1535	35	1.30	199	340	295	
4	7-24	1611	42	1.27	238	575	420	
522 Min. Total 8.7 hours

Figure 13. Temperature Histories for Various Column Locations (see Figure 12) for Test 2

balance unless the perturbations became so great that a substantial variation of the column temperature profile also resulted. The column wall temperature (T_w) was changing at a rate of less than $1^\circ\text{F}/\text{minute}$ as the column approached steady state so that thermal losses to the hardware were small. The column temperature profile appeared to approach a steady-state at time 2:20 and the test was terminated at 2:25.

The gas outlet temperature drift in Test 2 is thought to be an indication of poor liquid-gas contacting at the top of the column. This could be due to an excessively viscous liquid at the low inlet temperatures. The reason for the sudden decrease and recovery of temperatures T_1 and T_2 at the time 2:20 is not known. Channels of the cold inlet liquid could have formed and been deflected, momentarily, onto those temperature sensors or the readings could have been recorded incorrectly. The 25°F rise in the temperature profile of $(T_G)_{in}$ at 2:20 is not believed to be related to the above, especially since a deflection is not apparent in the intermediate temperature readings. Similarly, the dip in $(T_L)_{out}$ at 2:22 (shown by dashed line) was discounted as a real result as the neighboring temperature readings did not support such a temperature variation.

Measured gas and liquid flow rates and measured and calculated overall pressure drops are all plotted in Figure 14. The calculated pressure drops are based upon the manufacturers correlation for gas flow rates as measured at the column inlet. These were calculated from (assuming no liquid flow)

$$\Delta p = C \rho v^2 \quad (8)$$

where

- $C = 0.18$ (Reference 13)
- $\rho = \text{Gas density (lb/ft}^3\text{)}$
- $v = \text{Superficial gas velocity (ft/sec)}$
- $\Delta p = \text{Column pressure drop (in. H}_2\text{O/ft of packing)}$

¹³ *Chemical Engineer's Handbook*, op. cit. p. 18-22.

Figure 14. Experimental and Calculated Overall Pressure Drops and Gas and Liquid Rates for Test 2

The effect of an increase in gas temperature at constant mass flow rate is indicated by the curve for the temperature of 430°F. A correspondence between gas flow rate, $\dot{m}_G$, and measured pressure drop is apparent. However, a large discrepancy between the measured and calculated column pressure drops remains.

Assuming that the heat transfer fluid (Therminol 66) evaporates within the column to partial pressures of 60, 80 and 110 mm Hg (see Appendix B for vapor pressure and other properties of Therminol), higher column pressure drops can be estimated. As the molecular weight of the Therminol is 9.3 times that of nitrogen (M.W. ratio of 260/28), the assumed vaporization caused an increase in both the gas phase density and velocity. Thus, the observed increase in calculated pressure drop. Using the results of these calculations it can be deduced that the mean partial pressure of the Therminol in the column increased from ~80 mm Hg at time 2:05 to ~120 mm Hg at time 2:22. Thus, even though the observed temperature profile indicated that a steady-state had been reached and reasonable heat balances had been obtained for the column, the continued increase of the observed pressure drop over the duration of the run raises a question as to whether the composition of the gas + vapor phase had reached a steady state.

The one thing that becomes clear from the above results is that vaporization of the thermal fluid must be considered in assessing the measured pressure drop of the packed column. The physical explanation of this is illustrated in Figure 4 which shows vaporization of the Therminol in the lower section of the column and condensation of it in the upper part. For fixed inlet and outlet liquid and gas rates substantial increases in column pressure drop can occur because of increased internal column flows ΔG , for the gas phase, and ΔL , for the liquid phase. Also, it may no longer be possible to use the assumption of zero liquid flows in calculating column pressure drops (as indicated on Figure 14). For although this was reasonable for the low inlet

liquid flow rates, evaporation causes significant increases in ΔG and ΔL and leads to higher column pressure drops.

A heat balance for Test 2 based on measured gas and liquid flow rates and overall stream temperature changes is shown in Figure 15. Thermal energy provided by the gas phase must appear in the exiting liquid phase. In this case a discrepancy of ~10 percent is evident which is within experimental error. Measured ΔT 's ($T_G - T_L$) at the top and bottom of the column are shown in Figure 16. Using the overall column heat duty and a ΔT_{lm} temperature difference, an overall column heat transfer coefficient (U) can be calculated. (See Equation (3) and Table 5.) U_{AVG} for Test 2 was 1.6 Btu/hr ft²-°F.

Figure 17 shows that 83 percent of the effective heat transfer (liquid heating) took place in the top 50 percent of the column and that the ratio of the liquid heating rate in the top half of the column to that in the lower half was ~5:1. The liquid temperature at which vaporization effects become important is ~390°F (50 percent point). It is apparent, then, that the heat transfer coefficient must be a strong function of position within the column -- higher in the condensation region and lower in the evaporating region -- as pointed out in the discussion of Section III. Gas phase temperatures internal to the column were not measured, however, so that it was not possible to calculate local overall coefficients (U_{LOC}) for individual sections of the column and only U_{AVG} results are reported. Determination of U_{LOC} must await further refinement of the measurement technique for discriminating between gas and liquid phase temperatures within the packed bed.

TEST 1

Column temperature histories for Test 1 are shown in Figure 18. After a preliminary column heat-up period the gas rate ($\dot{m}_G$) was boosted by a factor of 6 at 3:00. The column appeared to be

Figure 15. Heat Duties Based on Gas and Liquid Phase Measurements for Test 2

Figure 16. Measured Temperature Difference Between Gas and Liquid Phases at Top and Bottom of Column for Test 2

Table 5. Calculation of U_{AVG} Based on
Test 2 Experimental Data

$U_{AVG} = \frac{\dot{q}}{A \Delta t_{lm}} = \frac{\dot{q}_A}{\Delta t_{lm}} \quad (\text{Eq. 3})$	
$\dot{q} = \frac{(\dot{m}C_p)_L \Delta t_L + (\dot{m}C_p)_G \Delta t_G}{2} = 19.0 \frac{\text{Btu}}{\text{sec}} = 69,400 \text{ Btu/hr.}$	
$\dot{q}_V = 69,400 / 6.0 \text{ ft}^3 = 11,580 \text{ Btu/hr-ft}^3$	
$\dot{q}_A = 11,580 / 63 \text{ ft}^2 / \text{ft}^3 = 180 \text{ Btu/hr-ft}^2 \text{ packing surface}$	
$\Delta t_{lm} = \frac{\Delta t_{top} - \Delta t_{bot}}{\ln \frac{\Delta t_{top}}{\Delta t_{bot}}} = 110^\circ \text{F}$	
$U_{AVG} = 180 / 110 = 1.64 \text{ Btu/hr-ft}^2 \text{-}^\circ \text{F}$

Figure 17. Measured Liquid Temperature Change vs. Column Position for Test 2

Figure 18. Temperature Histories for Various Column Locations (see Figure 12) for Test 1

approaching a steady state at time 3:20, however, the gas flow was interrupted for about 1/2 minute at time 2:25 to change supply bottles. Therefore, the test was continued until 3:30 to permit the column to fully stabilize.

Liquid and gas flow rates and measured and calculated pressure drops for this test are plotted in Figure 19. Again, changes in the gas flow rate are reflected by measured changes of the pressure drop, except at time 3:39. Observing the definite increase in column pressure drop starting at time 3:30 and upon re-evaluation of the temperature profile for T_3 on Figure 18, the increase in pressure drop may be associated with increased vaporization as discussed above for Test 2. Calculated heat duties and temperature differences for the top and bottom of the column are shown in Figures 20 and 21, and these results, along with those of Figure 18, indicate that a reasonable steady-state was achieved. Increases in T_3 and Δp at the end of the test do not support that conclusion, however.

TESTS 3 and 4

Based on the experimental results obtained in Tests 1 and 2, additional pressure drop instrumentation was added for Tests 3 and 4. These tests were run in sequence, the major difference being that the inlet gas temperature, which was held at 350°F (nominal for Test 3), was increased to 550°F in Test 4 in an attempt to improve gas/liquid contacting at the top of the column.

The column temperature histories for the various column positions are indicated in Figure 22. Test 3 was terminated at time 3:42. All temperatures were stable at that time except for T_w . As there had been no change in test conditions which could account for the abrupt change in T_w at time 3:38, a change in the thermal contact resistance was postulated as a probable cause. This would seem to be a reasonable explanation as the thermocouple,

Figure 19. Gas and Liquid Flow Rates and Calculated and Measured Pressure Drops for Test 1

Figure 20. Heat Duties Based on Gas and Liquid Phase Measurements for Test 1

Figure 21. Measured Temperature Difference Between Gas and Liquid Phases at Top and Bottom of Column for Test 1

Figure 22. Temperature Histories for Various Column Locations (see Figure 12) for Tests 3 and 4

Figure 23. Gas and Liquid Flow Rates and Experimental and Calculated Pressure Drops as a Function of Time for Tests 3 and 4

T_w , was merely placed in contact with, rather than welded to, the wall.

Test 4 was initiated at time 3:42 by resetting the gas heater to reach an inlet gas temperature of 550 F. It is immediately obvious from Figure 22 that a steady-state condition was never reached. The liquid inlet temperature was stable, but none of the other temperatures stabilized. This situation was not improved when at time 4:05 additional cold Therminol was added to the system through the top of the column. A large quantity of liquid had been held up within the packing, giving the false impression that the system was running low on Therminol. The addition of the cold Therminol caused large deflections in the temperature profiles T_1 , T_2 and T_3 , but its effect was apparent throughout the column. The test was terminated when the pressure drops within the column became excessive and when it became apparent that the liquid loading was increasing rapidly in the upper part of the column. The excess liquid hold-up was released from the packing upon termination of the test.

Pressure drop and mass flow rates for Tests 3 and 4 are plotted on Figure 23. Variations in measured pressure drops follow variations in gas flow rates for Test 3 but not for Test 4. In the latter test the effects of vaporization seem to have overwhelmed the effect of gas rate variability. The calculated pressure drop assumes zero vaporization of the Therminol, and is low by a factor of 2.0 for Test 3. This error increased to a factor of 6.0 at run termination of Test 4. External liquid and gas rates were held essentially constant so that the increasing column pressure drop had to be due to the increasing effect of vaporization within the column. This conclusion was further supported by the fact that 5.5 gallons of Therminol was released from the packing at run termination. This was an increase by a factor of 10 over the normal column hold-up that would be expected for the given gas flow rate.

Measured pressure drops for subsections of the column, as well as for the overall column pressure drop, are shown in Figure 24. The pressure drops for the three subsections are almost equal and steady until the start of Test 4. At that time the total pressure starts to increase steadily as a function of time. At time 4:08 the rates of increase of the pressure drops. (Δp_1 , Δp_6 , Δp_3) start to diverge. At run termination the ratio of Δp_3 to Δp_1 is 2.5. Δp_6 is intermediate between the two. The interpretation of these results is that the internal evaporation and condensation cycle has moved towards the top of the column. The smallest pressure drop is observed to occur within the lower third of the column.

The pressure drop data indicate that a steady state has not been achieved and that it is doubtful that one could be achieved in this column for the given inlet conditions. It is apparent that a steady-state certainly could not be achieved within the total pressure drop limitation of 10 inches of water assumed for this program.

Heat duties for Tests 3 and 4, as calculated separately from the gas and liquid, are plotted in Figure 25. A reasonably steady state appears to have been achieved for Test 3 (Time 3:00-3:39). However, no such statement can be made in regard to Test 4.

The percent liquid temperature change as a function of percent column packing for Test 3 is shown in Figure 26 for three test times. An upward drift in this profile with time is apparent and at the two later times (3:30 and 3:42) the reading from the thermocouple at position four (62.5%) is deflected slightly upwards. This latter feature could be a real result, but it seems more likely that it is due to an incorrect output of the thermocouple. This thermocouple was added, on short notice, especially for Tests 3 and 4, and its operation was not as carefully verified as the others which were used. If this reading were substantially high, the actual column profile might approach

Figure 24. Measured Overall and Incremental Pressure Drops for Tests 3 and 4

Figure 25. Experimental Gas and Liquid Heat Duties vs. Time for Tests 3 and 4

Figure 26. Column Temperature Profiles for Test 3

linearity over the bottom 75% of the packing (see Figure 26). The column temperature profile for the test time of 3:35 is also plotted in Figure 27 along with column profiles of Tests 1 and 2.

For Tests 1 and 2 the effectiveness of the top 50 percent of the packing in facilitating heating of the liquid is almost 5 times as great as the bottom 50 percent. For Test 3 the effectiveness ratio of the two halves is almost 1:1. However, the effectiveness of the top 62 percent (defined by the knee of the curve) of the packing in Test 3 compared to the bottom 38 percent is ~2.5.

It will be recalled that Test 3 was run with a low gas inlet temperature to minimize the effects of evaporation and condensation on the heat transfer. If only sensible heat transfer had been involved, the liquid temperature profile would be almost linear (see discussion in Section III). The experimental profile obtained is not linear, but the demarcation between the evaporating and condensing zones is not so prominent as is the case for Tests 1 and 2. The conclusion is that although evaporation effects have been reduced in Test 3, they have not been eliminated.

Overall heat duties, heat duties/unit area, and heat transfer coefficients are shown in Table 6. A comparison of experimental results to the magnitude of calculated heat transfer coefficients is also presented there. Although it is recognized that the overall heat transfer coefficients may be a strong function of position within the column, gas phase temperatures, which are required to calculate U , were not available for internal column positions. Therefore, only a mean overall U is reported. The predicted overall coefficients are for column conditions ranging from 100-500°F for which it was assumed no evaporation or condensation took place.

For Test 3, where evaporation and condensation were minimized, the measured coefficient was about 25% of the coefficient

predicted by Biphase. Considering the fact that (1) the mass transfer correlations from which the prediction was made represents the mass transfer data to ± 20 percent; (2) the Reynold's analogy was used under conditions for which it is not strictly applicable (a considerable part of the pressure drop in packed column is due to form drag); and (3) no account was taken for the effect of evaporation and condensation on the heat transfer coefficient, this level of disagreement is probably not surprising.

Figure 27. Measured Liquid Temperature Change vs. Column Position for Tests 1, 2, and 3

Table 6. Summary of Experimental Heat Duties and U_{AVG}

Test	$\dot{q}$ (Btu/hr)	$\dot{q}_v$ Btu/hr-ft ³	$\dot{q}_A$ (Btu/hr-ft ²)	$(\Delta t)_{lm}$ °F	U_{AVG} (Btu/hr-ft ² °F)	$U_{predicted}$ (Btu/hr-ft ² °F)	
						Biphase	McEligot ¹¹
1		14,370	228	68	3.2	--	--
2		11,360	180	110	1.6	--	--
3		6,870	110	32	3.4	13.0	9.1 - 18.5
4	Steady-state not achieved						

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Conclusions are stated under three headings: test equipment, heat transfer, and system design considerations. Successful operation of the equipment has prompted recommendations that additional experimental measurements be made which would be useful for developing the diesel engine bottoming cycle.

Test Equipment

An experimental direct contact heat exchanger was assembled and was operated successfully. The equipment is of convenient size for testing with available diesel engines, and is available for further test programs. The gas/liquid temperature probes were effective in measuring liquid temperatures, but in the test time available, efforts to discriminate between gas and liquid temperature within the packed bed were not successful. Additional testing will be required to complete an evaluation of the potential effectiveness of the temperature/sampling probes.

Heat Transfer

The results for column temperature profile, pressure drop and heat transfer data reported are not completely unexpected but seem to be unique in the published literature. The liquid temperature profile indicated that distinct evaporation and condensation regions exist such that

$$\frac{\text{Rate of liquid heating in condensing zone}}{\text{Rate of liquid heating in evaporating zone}} \approx \frac{4}{1}$$

The resulting overall heat transfer coefficient that can be calculated from these data is substantially less than that which was predicted assuming no evaporation. Thus, if presently known analytical correlations were used for design, undersized equipment would result. The experimental data can be used for estimating the design requirement of a direct contact heat exchanger for a diesel bottoming cycle using Therminol 66.

System Design Considerations

Test results showed that the practical upper temperature limit to which a liquid may be heated by direct contact with a gas may be controlled by hydraulic (Δp) limitations rather than by wet bulb temperatures. The maximum temperature to which liquid Therminol 66 was heated in these tests was 450F using a gas at 575 F, although experimental conditions were not optimized. If it is assumed that a maximum liquid temperature of 500°F (compared to 600°F for the reference cycle) can be attained with a gas temperature of 700°F, the Biphase cycle efficiency would be reduced 3 percentage points from the reference cycle efficiency (27%).

Some ageing of Therminol 66 was observed after 8 hours of operation. Results of its long-time contact with diesel exhaust and with water have not been evaluated.

Data obtained for the N₂/Therminol 66 system represent the second system (air/water is the other) for which data are available in the published literature on direct-contact heat transfer of gas-liquid phases in commercial contacting equipment. Some conclusions can possibly be drawn from these two data points. However, the development of a general theory applicable to other fluids and to other conditions, and which can be used for optimization analyses, will require additional information which can be obtained by additional extended duration runs.

RECOMMENDATIONS

1. Perform direct-contact heat transfer experiments to obtain data under conditions where evaporation/condensation occurs by operating the direct contact exchanger either with a high volume air compressor or with a 250 HP diesel engine. Obtain specific data as required to develop an expanded theory of direct contact heat exchanger design.
2. Continue development of the gas/liquid temperature probe as an aid in understanding heat exchanger performance.
3. Make exploratory runs with other heat transfer fluids, including petroleum-based fluids, and especially including fluids with lower vapor pressures than Therminol 66. Assess safety (flammability) and other properties.
4. Conduct endurance tests with the selected heat transfer fluid, including exposure to diesel exhaust and water.
5. Instrument the open top of the tower so that the amount of heat transfer fluid discharge to the atmosphere may be determined. Develop hardware to minimize this loss.

APPENDIX A
EXPERIMENTAL DATA

TABLE A-1

Raw Data for Gas and Liquid Flow Rates and
for Heat Duties for Test 1

Rotameter Factors:

100 = 275 SCFM

Nitrogen Gas @ SC

Run	Temp. In T_{2F}	Temp. Out T_{2F}	ΔT $T_2 - RT_2$ F	Orifice Meter						Rotameter				Flow lb/sec	Heat Duty BTU/sec	ΔT_{top} $T_2 - RT_2$	ΔT_{bott} $RT_2 - RT_4$
				F_g	T_{corr}	P psig	P_{corr}	$F_{g,corr}$ SCFM	$F_{g,calib.}$ SCFM	F_{gr}	T_{corr}	P_{corr}	F_{gr} SCFM				
2:25	430	215	215	62	0.99	106	1.02	62.6	-	18	1.0	1.348	66.7	0.0868	4.72	0	180
2:35	485	200	285	62	1.0	108	1.03	63.8	-	18	1.0	1.385	68.6	0.0829	5.98	20	215
2:50	570	140	430	65	1.0	113	1.04	67.6	-	18	1.0	1.409	69.7	0.0842	9.16	5	285
3:12	575	155	420	213	1.034	105	1.02	225.0	190	31	1.034	2.306	203.3	0.245	26.0	10	160
3:20	570	165	405	212	1.034	104	1.02	224.0	190	31	1.034	2.277	200.7	0.242	24.8	27	148
3:30	575	160	415	209	1.030	98	0.99	213.0	173	30	1.030	2.247	190.9	0.230	24.1	22	150
3:35	560	165	395	211	1.032	101	1.01	220.0	178	31	1.032	2.277	200.3	0.241	24.1	23	145
3:37	580	170	410	212	1.032	103	1.02	223.0	183	31	1.032	2.292	201.6	0.243	25.2	25	152

Date: 7-7-78

TABLE A-2

Raw Data for Gas and Liquid Flow Rates and
for Heat Duties for Test 2

Rotameter Factors:

100 = 275 SCFM

Nitrogen Gas @ SC

Run	Temp. In RT ₂ F	Temp. Out RT ₃ F	ΔT RT ₂ -RT ₃ F	Orifice Meter						Rotameter				Flow lb/sec	Heat Duty BTU/sec	ΔT ^{top} RT ₃ -RT ₁	ΔT ^{bott} RT ₂ -RT ₄
				F _g	T _{corr}	P psig	P _{corr}	F _g corr	F _g calib. SCFM	F _{gr}	T _{corr}	P _{corr}	F _{gr} SCFM				
11:05	750	185	565	121	1.0	101	1.0	122	103	24.0	1.0	1.843	122	0.147	21.0	50	295
2:05	635	170	465	203	1.02	94	0.97	201	162	30.0	1.02	2.22	187	0.226	26.6	50	215
2:10	580	190	390	208	1.02	96	0.98	208	165	31.0	1.02	2.24	195	0.236	23.3	70	140
2:15	545	210	335	211	1.02	98	0.99	213	173	31.5	1.02	2.254	199	0.240	20.3	90	110
2:20	x	220	x	214	1.03	100	1.0	220	178	31.5	1.03	2.269	202	0.244	x	110	x
2:22	530	230	300	218	1.03	101	1.0	225	183	32.0	1.03	2.284	206	0.249	18.9	120	97
2:25	525	235	290	206	1.03	92	0.96	204	165	31.0	1.03	2.177	191	0.231	16.9	125	97

Date: 7-13-78

TABLE A-3
Raw Data for Gas and Liquid Flow Rates and
for Heat Duties for Tests 3 and 4

Rotameter Factors:
100 = 275 SCFM
Nitrogen Gas @ SC

Run	Temp. In RT ₂ F	Temp. Out RT ₃ F	ΔT RT ₂ -RT ₃ F	Rotameter						Flow lb/sec	Heat Duty BTU/sec	ΔT ^{top} RT ₃ -RT ₁	ΔT ^{bott} RT ₂ -RT ₄
				Fgr	T _w	T _{corr}	P ₃ psig	P _{corr}	Fgr SCFM				
3:05	370	205	165	31.0	50	1.02	52.0	2.130	185.2	0.224	8.7	0	145
3:10	410	190	220	31.5	45	1.02	53.0	2.146	189.6	0.229	12.7	10	120
3:18	365	165	200	32.5	40	1.03	56.0	2.193	201.9	0.244	12.3	30	55
3:25	345	165	180	31.5	39	1.03	50.0	2.098	187.1	0.226	10.3	25	45
3:30	345	160	185	32.0	40	1.03	50.0	2.098	190.2	0.230	10.8	20	50
3:35	340	160	180	33.0	40	1.03	52.0	2.130	199.1	0.241	11.0	20	45
3:38	340	165	175	-	-	-	-	-	-	-	-	-	-
3:42	335	165	170	32.5	40	1.03	53.0	2.146	197.6	0.239	10.3	25	40
3:53	460	170	290	34.0	40	1.03	70.0	2.40	231.0	0.279	20.5	30	100
3:57	495	185	310	34.0	40	1.03	73.0	2.44	235.0	0.284	22.3	40	125
4:00	530	185	345	33.5	40	1.03	75.0	2.47	234.0	0.283	24.7	40	140
4:08	575	170	405	33.5	40	1.03	77.5	2.504	237.6	0.287	29.4	25	170
4:11	575	185	390	33.5	40	1.03	78.0	2.51	238.0	0.288	28.4	40	155
4:13	570	205	365	33.5	40	1.03	78.0	2.51	238.0	0.288	26.6	60	115
4:17	565	255	310	33.5	40	1.03	78.0	2.51	238.0	0.288	22.6	105	115

Date: 2-24-78

APPENDIX B
PROPERTIES OF THERMINOL 66

APPENDIX B
PROPERTIES OF THERMINOL 66

**... wide-range liquid phase
heat transfer fluid for
non-pressurized indirect
heating to 650°F.**

Heat transfer fluids are intended only for *indirect* heating purposes. Under no circumstances should this product contact or in any way contaminate food, animal feed, food products, food packaging materials, pharmaceuticals or *any items which may directly or indirectly be ultimately ingested by humans*. Any contact may contaminate these items to the extent that their destruction may be required. Precautions against ignitions and fires should be taken with this product.

Monsanto

"Nothing contained herein is to be construed as a recommendation to use any product in conflict with any patent. MONSANTO MAKES NO WARRANTIES AS TO THE FITNESS OR MERCHANTABILITY OF ANY PRODUCT REFERRED TO, no guarantee of satisfactory results from reliance upon contained information or recommendations, and disclaims all liability for any resulting loss or damage."

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800 North Lindbergh Blvd., St. Louis, Missouri 63166

Therminol 66 . . .

Typical Properties

is a high-performance synthetic heat transfer fluid offering low-temperature pumpability (0°F.) along with outstanding high-temperature performance — up to 650°F. Therminol 66 is ideally suited to replace organic fluids which have lower boiling points and must operate under pressure at 650°F.

This fluid is designed for use in non-pressurized indirect heating systems. It delivers efficient, dependable process heat with no need for high pressures, costly "extra" equipment, or continuous supervision.

Therminol 66 is not classified as a fire-resistant heat transfer fluid. Consequently, the use of protective devices may be required to minimize fire risk. The insurer of your property should be consulted relative to this matter.

To minimize fluid oxidation, Therminol 66 systems should be blanketed with an inert atmosphere. A system relief valve should also be provided.

Therminol 66 offers long service life within its recommended operating temperature range, and is non-corrosive to metals commonly used in the design of heat transfer systems.

Composition	Modified Terphenyl
Appearance	Oily liquid, practically colorless
Odor	Faint, characteristic
Pour Point	—18°F.
Density @ 75°F.	8.35 lbs./gal.
Flash Point	355°F.
Fire Point	382°F.
AIT	705°F.
Coefficient of Expansion	0.00070 cc/cc/°C.
Boiling Range:	
10%	644°F.
90%	745°F.
Average Molecular Weight	240

Variations of Properties With Temperature

Temperature		Density			Specific Heat		Thermal Conductivity		Viscosity		Vapor Pressure	
°F	°C	lbs./gal.	lb./ft. ³	Kg./m. ³	BTU/lb. °F	Kcal./Kg. °C	BTU/ft. hr. °F	Kcal./m. hr. °C	lb./hr. ft.	cs	mmHg. absolute	Kg./cm. ³
0	—18	8.67	64.9	1040	0.320	0.320	0.0720	0.1072	150000	50000		
50	10	8.51	63.6	1020	0.350	0.350	0.0711	0.1058	617	250		
100	38	8.34	62.4	1000	0.380	0.380	0.0703	0.1046	67.8	28.0		
150	66	8.14	60.9	975	0.405	0.405	0.0695	0.1034	23.6	10.0		
200	93	7.91	59.3	950	0.430	0.430	0.0687	0.1022	10.1	4.40	0.1	—
250	121	7.77	58.0	930	0.455	0.455	0.0678	0.1008	5.86	2.60	—	—
300	149	7.59	56.8	910	0.480	0.480	0.0670	0.0997	3.75	1.70	2.0	0.003
350	177	7.39	55.2	885	0.505	0.505	0.0662	0.0985	2.57	1.20	—	—
400	204	7.17	53.6	860	0.530	0.530	0.0653	0.0972	1.88	0.90	20.0	0.027
450	232	7.04	52.5	840	0.555	0.555	0.0645	0.0959	1.40	0.69	50.0	0.068
500	260	6.75	50.5	810	0.580	0.580	0.0637	0.0948	1.08	0.55	100.0	0.136
550	288	6.62	49.5	793	0.605	0.605	0.0628	0.0935	0.87	0.46	200.0	0.272
600	316	6.42	48.1	770	0.630	0.630	0.0620	0.0923	0.82	0.44	350.0	0.476
650	343	6.24	46.8	750	0.655	0.655	0.0613	0.0912	0.65	0.36	760.0	1.034
700	371	6.09	45.6	730	0.680	0.680	0.0605	0.0900	0.49	0.28	1000	1.360

Therminol 66—Physical Properties

Therminol 66—Heat Transfer Coefficients

Therminol 66—Pressure Drop

Therminol 66—Safety of Handling

Therminol 66 is virtually non-toxic and non-irritating, posing no special handling problems. It is not absorbed through the unbroken skin in significant quantities, is non-irritating to the skin and only mildly irritating if eye contact occurs. Immediate flushing of the eye with copious amounts of water will avoid irritation or after-effects. It is suggested that Therminol 66 be washed off the skin with soap and water as soon as possible after contact, but no serious irritation should be observed. Handled like any other industrial chemical, Therminol 66 is quite safe to store and use.

Therminol 66 vapors are not toxic, but may cause discomfort if coming off of heated fluid. There is no vapor exposure problem when transferring the fluid from its shipping container to the heat transfer system. On the other hand, vapors emitted by

Therminol 66 heated to elevated temperatures may be mildly irritating upon prolonged exposure. In heat transfer installations, the fluid is used in a closed, non-pressurized system free from leaks and with the expansion tank vent trapped so as to condense any vapors. Consequently, there should be little or no opportunity for workers to come in contact with vapors.

While Therminol 66 poses no serious problems with respect to the environment, as a concerned supplier to industry, Monsanto urges the user to maintain a tight system, to correct leakage promptly, and to exercise care in the handling and disposal of this and all other such products. A tight maintenance program not only protects the environment, but keeps employees comfortable, the working area clean, and the system running smoothly.