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SUBJECT: Volatility Pilot Plant Modifications--
Hydrogen Fluoride Condensers, FV-2004, FV-2005
TO: R. P. Milford
FROM: S. Mann

COPY NO. 17

Abstract

Off-gas from the hydrofluorinator will be cooled and 94% of the hydrogen fluoride condensed by two heat exchangers connected in series. The first unit, water-cooled, discharges gas and condensed vapor at 50 to 65°F. The second unit, freon-cooled, discharges condensed vapor and noncondensable hydrogen and nitrogen at -60 to -75°F. This report concerns a design description of the condensers and a heat transfer evaluation. The condensers will be fabricated at ORNL.

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12/23/58 *Arthur L. Davis*
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1.0 INTRODUCTION

Off-gas from the hydrofluorinator (dissolver) contains hydrogen fluoride, hydrogen, and nitrogen in variable amounts depending on the dissolution rate.¹ The reaction initially proceeds rather rapidly being about three-fourths complete in one-fourth of the allotted reaction time.² The reaction rate steadily decreases with increasing time. The initial phase of the reaction is characterized by the evolution of significant quantities of hydrogen and unreacted HF, while in the latter phase of the run, the off-gas consists almost entirely of HF.

To prevent using a larger refrigeration unit the first condenser, cooled with 40°F water, is designed to remove 70% of the heat. The freon-cooled unit will cool the noncondensable gas and the condensed vapor to -60°F, discharging the liquid into the freon-cooled accumulator vessel. One freon refrigeration unit serves the freon-cooled condenser and accumulator vessel. A separate water refrigeration unit is provided for the water-cooled condenser.

Design of a condenser that at one time acts only as a gas cooler and later serves as both a cooler and vapor condenser makes fins in contact with the process stream undesirable. Design requirements are a large cooling surface area, a minimum liquid film resistance, and a sufficient gas velocity to lower the gas film resistance. The condenser design shown in Fig. 1 appears to be satisfactory.

All calculations, unless indicated otherwise, were made by the Engineering and Mechanical Division, Chemical Design Section (available in the files of W. A. Bush).

2.0 OFF-GAS CONDITIONS

The condenser operation was evaluated by assuming three different off-gas conditions. If the hydrofluorination reaction proceeds at a constant rate until complete in nine hours, the off-gas will contain 55 lbs/hr HF and 0.448 lb/hr hydrogen. A more realistic case is a variable reaction rate in which the hydrofluorination reaction is essentially complete in three hours. Average off-gas composition during the first three hours is 33 lbs/hr HF and 1.34 lbs/hr hydrogen. During the remaining six hours of the allotted reaction time the off-gas contains 60 lb/hr HF. A 5 scf/hr nitrogen instrument purge is present in each case.

The required heat removal was calculated for the water-cooled condenser with the arbitrary assumption that it decreased the gas temperature to 50°F and caused the necessary condensation. Similar calculations were made for the freon-cooled condenser which discharges gas and liquid at -60 to -75°F. Table 1 summarizes the gas conditions at the inlet and outlet of each condenser. Entrance temperatures at the first condenser were calculated by assuming that the gases left the hydrofluorinator at 1112°F and were partially cooled in passing through the uninsulated line to the condenser.

¹ $4\text{HF} + \text{Zr} \rightarrow \text{ZrF}_4 + 2\text{H}_2$ The nitrogen is from instrument purges.

² UNOP Data, R. W. Horton

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FIG. 1 OFF - GAS COOLER-CONDENSER, FV-2004, FV-2005

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In describing the three off-gas conditions the following terminology is used. The 9-hr average refers to the off-gas condition if the hydrofluorination reaction rate were constant until complete in nine hours. The 3-hr initial phase refers to the off-gas condition during the first three hours of the reaction assuming that the reaction went to completion in three hours at a constant rate. The six hours remaining in the allotted reaction time is designated as 3-hr final phase.

Table 1

Gas Conditions

	9-hr average	3-hr initial phase	3-hr final phase
<u>Water-Cooled Condenser</u>			
temperature in	328°F	289°F	347°F
temperature out	50°F	50°F	63°F*
total HF flow rate	51.0 lb/hr	33.1 lb/hr	60.0 lb/hr
HF condensed	25.9 lb/hr	none**	56.4 lb/hr
HF not condensed	25.1 lb/hr	33.1 lb/hr	3.6 lb/hr
hydrogen	0.448 lb/hr	1.34 lb/hr	0 lb/hr
<u>Freon-Cooled Condenser</u>			
temperature in	50°F	50°F	63°F
temperature out	-75°F	-75°F	-75°F
HF condensed	24.5 lb/hr	31.3 lb/hr	3.6 lb/hr
HF not condensed	0.64 lb/hr	1.85 lb/hr	0.038 lb/hr
hydrogen	0.448 lb/hr	1.34 lb/hr	0 lb/hr

*The minimum outlet temperature based on the available heat transfer area.

**Gas stream is not saturated at 40°F.

3.0 CONDENSER HEAT DUTY

3.1 Water-Cooled Condenser

The condenser was divided into three effective zones. The first zone, beginning at the gas inlet, was assumed to be a gas cooling zone with the bulk temperature of the gas ranging from the inlet temperature to 160°F. No condensation or association of the HF molecules was assumed to occur. In the next zone the gas was cooled to 70°F with the corresponding heat of association and sensible heat removed. Additional heat of association, sensible heat, and the heat of condensation were removed in the last section and the gas and condensed vapor discharged at 50°F or 63°F.

Required heat removal in each temperature zone is given in Table 2.

Table 2

Water-Cooled Condenser Heat Duty--Btu/hr

	9-hr average	3-hr initial phase	3-hr final phase
Zone 1 (entering temp. to 160°F)	3269	2090	3939
Zone 2 (160°F to 70°F)	27,752	18,258	32,497
Zone 3 (70°F to 50°F)*	5685	819	11,562*

3.2 Freon-Cooled Condenser

Table 3 lists the heat removal necessary to decrease the temperature of the gas-liquid mixtures entering the freon-cooled condenser to -75°F.

Table 3

Freon-Cooled Condenser Heat Duty--Btu/hr

	9-hr average	3-hr initial phase	3-hr final phase
gas cooling	228.6	662.3	12.4
liquid cooling	6370	4135	8280
heat of condensation	4300	5450	624
heat of association	2625	1700	3690

*The temperature is lowered to 63°F in the 3-hr final phase.

4.0 CONDENSER AREA REQUIREMENTS

4.1 Water-Cooled Condenser

Cooling water at 40°F flows at a combined rate of 9.4 gpm through the four paths indicated in Fig. 1. Flow rates through the coiled tubes correspond to a pressure drop of 30 psi. The required area for each temperature zone was determined by calculating log mean temperature differences over each zone and assuming overall heat transfer coefficients of 150 Btu/hr ft² °F for the condensation zone and 10 Btu/hr ft² °F for the gas cooling zone.

$$A = \frac{q}{U \Delta t}$$

q = heat transfer duty for each zone, Table 2, Btu/hr
 U = overall heat transfer coefficient, Btu/hr ft² °F
 Δt = log mean temperature difference for each zone, °F
 A = required surface area of each zone, ft²

Area requirements for the water-cooled condenser depend on the gas rate as shown in Table 4. A heat transfer area of 65.1 ft² is available indicating that the condenser is satisfactory for each phase of the reaction.

Table 4

Water-Cooled Condenser Area Requirements

	9-hr average	3-hr initial phase	3-hr final phase
Zone 1	1.9 ft ²	1.2 ft ²	2.2 ft ²
Zone 2	47.2	29.3	58.0
Zone 3	<u>9.2</u>	<u>4.5</u>	<u>4.6</u>
Total area required	58.3 ft ²	35.0 ft ²	64.8 ft ²

4.2 Freon-Cooled Condenser

Freon at -80°F circulates through the four paths at a combined flow rate of 17 gpm. The unit is identical to the water-cooled condenser except the length is 30 in. Area requirements were determined in a manner similar to the water-cooled design. A heat transfer coefficient of 10 Btu/hr ft² °F was used when cooling the gas and a coefficient of 150 Btu/hr ft² °F when removing the heat of condensation. Area requirements are listed in Table 5. Availability of 16.1 ft² of heat transfer area indicates that the freon-cooled condenser is satisfactory for each phase of operation.

Table 5

Freon-Cooled Condenser Area Requirements

	9-hr average	3-hr initial phase	3-hr final phase
gas cooling	0.64 ft ²	1.89 ft ²	0.03 ft ²
liquid cooling	1.20	0.79	1.50
heat of condensation removal	<u>1.30</u>	<u>1.36</u>	<u>0.78</u>
Total area requirement	3.14 ft ²	4.04 ft ²	2.31 ft ²

5.0 MODIFIED EVALUATION METHOD

The water-cooled condenser was evaluated using a different approach.³ The latter calculations indicated that the water-cooled condenser would lower the off-gas temperature to 50°F for each phase of the reaction.

No condensation occurs in the 3-hr initial phase, thus allowing treatment as a gas cooler. A relationship by Chilton and Colburn⁴ was used to calculate a gas film coefficient.

$$h = j c G \left(\frac{K}{c \mu} \right)^{2/3}$$

h = gas film coefficient
c = heat capacity of vapor
G = mass flow rate

K = vapor thermal conductivity
 μ = vapor viscosity
j = function of Reynolds number
as reported in (1).

Temperature range 60°F to 350°F

Re = 16,000 (approximate)

c = 1.98 Btu/lb °F (An average between 5.43 Btu/lb °F for the range 70°F to 160°F and 0.348 Btu/lb °F for the range 160°F to 350°F)

h (gas film) = 12.1 Btu/hr ft² °F

Area required = 24 ft²

In the 3-hr final phase the gas stream consists almost entirely of HF. Assuming that a condensate film forms on surfaces that are below the dew point of the vapor, and that the film continues to grow until the surface temperature is at the dew point, the following heat transfer expression may be written.

³J. L. Whitten, Process Design Section, Chemical Technology Division

⁴T. H. Chilton, A. P. Colburn, Ind. Eng. Chem., 26, 1183 (1934)

$$q = U A \Delta t = U A (t_s - t_c)_{\log \text{ mean}}$$

t_s = dew point of vapor (i.e., the boiling point for a pure vapor)

t_c = cooling water temperature

for:

$$q = 48,000 \text{ Btu/hr}$$

$$t_s = 75^\circ\text{F (boiling point at 17.3 psia pressure)}$$

$$t_c = 40^\circ\text{F inlet, } 49^\circ\text{F outlet}$$

$$U = 240 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

Area required = 6.5 ft^2 (This area refers to the cooling coils and not the jacket.)

Area requirements for the 9-hr average off-gas condition should fall between those for the 3-hr initial phase and the 3-hr final phase.

6.0 DESIGN OPERATION

The same design, Fig. 1, is used for both condensers, the only difference being in length. The water-cooled condenser shell is 102 in. long and the freon-cooled unit 30 in. in length. The process gas stream flows through the 0.156 ft^2 annulus between a 2-1/2-in. NPS center pipe and a 6-in. NPS shell. A coolant jacket surrounds the shell. In the annular space there are two concentric helical coils, the inner coil made of 1/4-in. NPS pipe and the outer coil of 3/8-in. NPS pipe. Water (or freon) circulates in parallel through the jacket, each of the coiled tubes, and through the 2-1/2-in. central tube.

An area of 0.0374 ft^2 is available for gas flow, giving gas flow rates of $1600 \text{ lb/ft}^2 \text{ hr}$ at 60 lb HF per hour.

Two coolant circuits are used as shown in Fig. 1. One circuit includes the jacket and 2-1/2 in. central tube, the other circuit consists of the cooling coils. Flow rates in each circuit are equalized to provide a 30 psig pressure drop for each path.

Condenser dimensions are given in Table 6.

Table 6

Condenser Dimensions

	FV-2004 Water Cooled	FV-2005 Freon Cooled
Shell length (including end plates)	102 in.	30 in.
pipe size	6 in. NPS	6 in. NPS
Jacket length	99 in.	25-1/2 in.
inside diameter	7-1/16 in.	7-1/16 in.
thickness	1/8 in.	1/8 in.
Coil (1/4 in.) diameter (center line)	3-5/8 in.	3-5/8 in.
Coil (3/8 in.) diameter (center line)	5-1/8 in.	5-1/8 in.
Number of coils (1/4 in.)	118	29
Number of coils (3/8 in.)	118	29
Inside spacer pipe size	2-1/2 in. NPS	2-1/2 in. NPS

7.0 MATERIAL AND DESIGN SPECIFICATIONS

Inconel, (or Monel), depending on availability will be used for all surfaces in contact with HF. With the exception of end plates and jacket which will be 1/4 and 1/8 in. rolled plate, respectively, all parts will be NPS pipe. Use of pipe at the design pressure indicated in Table 7 is within Boiler Code requirements. Jacket stress calculations are satisfactory. Both vacuum and hydrostatic tests will be performed.

Table 7

Design and Operating Conditions

	Operating Conditions	Design Range
Freon temperature	-80°F	-80°F to room temp.
Cooling water temperature	40°F	40°F to 212°F max.
Pressure	2-5 psig (15 psig)*	50 psig

*Decontamination solution head

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SM:atm

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