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### EVACUATION SYSTEMS FOR STEAM SURFACE CONDENSERS: VACUUM PUMPS OR STEAM JET AIR EJECTORS?

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#### ABSTRACT

In a steam power plant, steam from the steam turbine is condensed in a water cooled or air cooled condenser that operates under vacuum. The condensing capacity of the condenser is impaired by the presence of air. Air leaks into the condenser from flanged connections, turbine seals, valves and other equipment connected to the condenser. The air tends to collect in the condenser and impact its condensing capability. This trapped air has to be continuously evacuated to preserve the condensing capacity of the condenser.

The air can be evacuated from the condenser using the steam jet air ejector system or the vacuum pump system. The vacuum pump is driven by an electrical motor. The steam jet air ejector is driven by motive steam. In certain low suction pressure applications, a hybrid system consisting of a steam jet air ejector and vacuum pump or a three stage ejector system is used for evacuating the air from the condenser.

The evacuation packages perform two distinct services namely hogging and holding. During startup, or hogging operation, the evacuation system removes air from the steam space of the condenser and steam turbine. The pressure in the steam space is reduced from atmospheric pressure to typically 10.0" HgA or a pressure specified by the steam turbine supplier in about 30 minutes. During normal or "holding operation" with the steam turbine in service, the evacuation system removes a specified amount of air from the condenser.

The suitability of vacuum pump or steam jet air ejector systems for a given application depends on the availability of motive steam during startup, the costs associated with the usage of steam or electricity and the preferences of the end user. Each system has its advantages and disadvantages. In each case, there are numerous design details that must be addressed to ensure that the selected system meets the evacuation needs for the condenser.

This paper examines the various configurations of evacuation systems and discusses their suitability for the wide ranging operating scenarios in the condenser. A broad background on the design and operation of the evacuation system is included to assist the end user in making the proper selection of the evacuation system.

#### INTRODUCTION

##### Operating Principle: Steam Jet Air Ejector System

In a steam jet air ejector, the motive steam emerging from the steam nozzle entrains the air-vapor mixture from the suction connection. The resulting mixture flows through the diffuser. At the exit of the diffuser, the pressure is substantially higher than the initial suction pressure. The above represents the operating principle of the first stage ejector, second stage ejector and the steam jet hogger. Steam-air mixture from the first stage ejector is admitted to the inter condenser wherein a majority of the steam is condensed. The uncondensed steam and air mixture from the inter condenser flows into the second stage ejector. The steam air mixture exiting the second stage ejector at pressure above atmospheric pressure enters the after condenser wherein a significant portion of the steam is condensed. The uncondensed steam air mixture is vented to the atmosphere. The condensate from the condenser hotwell flows through the tubeside of the inter and after condenser.

Each ejector system consists of two first stage ejectors and two second stage ejectors. One first stage ejector and one second stage ejector constitute "one element". The ejector system has twin elements representing 200% capacity.

The two stage twin element steam jet air ejector, hogger, inter and after condenser, valves and instruments are usually pre-piped, pre-valved and mounted on a common skid.

A typical piping & instrumentation diagram of the manual and automatic ejector system is included in Figures 1 and 2.

## **Operating Principle: Liquid Ring Vacuum Pump System**

In a liquid ring vacuum pump, the steam-air mixture is compressed by rotating a vanned impeller located eccentrically within a cylindrical casing. Cold condensate is introduced to the pump. The centrifugal acceleration creates a moving cylindrical ring against the inside of the casing. The eccentricity between the impeller's axis of rotation and the casing geometric axis results in a cyclic variation of the volume enclosed by the vanes and the ring.

Steam-air mixture is drawn into the pump at the inlet connection located at the end of the casing. The steam in the steam-air mixture condenses on the cold liquid ring. The reduction in volume caused by the impeller rotation compresses the steam-air mixture which exits through the discharge connection located at the end of the casing.

Due to the large compression ratio, liquid ring vacuum pumps are designed with two stages. During hogging, only the first stage is in use. Single stage pumps do not evacuate condenser pressures below 5" HgA. Both stages are in use for lower evacuation pressures encountered in normal operation.

Water-air-vapor mixture from the vacuum pump flows into the separator tank wherein the air and water are separated. The air is vented to the atmosphere. In a seal water heat exchanger, the heated seal water is cooled by circulating water or service water. The separator tank acts as a silencer.

Typically two 100% vacuum pumps are provided. One vacuum pump performs the evacuation duties while the other pump remains on standby. In certain applications three 50% pumps are deployed. Two 50% pumps are pressed into service and one 50% pump remains on standby. During hogging, all pumps are in operation. At a pressure specified by the turbine supplier, one vacuum pump is taken out of service. The other pump or pumps, as the case may be, remain in operation and evacuate air from the condenser.

Each vacuum pump with motor, seal water heat exchanger, separator tank, instruments and control panel is pre-valved, pre-piped, pre-wired and mounted on a common skid.

A typical piping & instrumentation diagram of the vacuum pump system is included in Figure 2.

## **DESIGN FEATURES COMMON TO BOTH EJECTOR SYSTEMS AND VACUUM PUMP SYSTEMS**

### **Subcooling of Air-vapor Mixture in the Condenser**

Per HEI standards, the venting equipment is sized for subcooling of air-vapor mixture for a value greater of 7.5°F or 0.25 times the difference between saturation temperature corresponding to design operating pressure of venting minus the circulating water inlet temperature. All steam surface condensers are equipped with an air cooling zone typically located in the coldest tube pass. In the air cooling zone, the vapor is stripped from the air-vapor mixture and the subcooled air-vapor mixture exits the condenser. Higher

subcooling and reduced amount of vapor in the air-vapor mixture result in improved performance of the evacuation system.

### **Condensation of Steam from the Air-vapor Mixture**

In the ejector system, hotwell condensate flowing through the tubeside of the inter and after condenser condenses the steam from the steam-air mixture flowing through the shellside. In the vacuum pump system, the vapor in the air-vapor mixture condenses on the cold seal water ring. The heated seal water is cooled by the circulating water in a shell & tube or plate & frame heat exchanger.

The use of hotwell condensate in the ejector system and circulating water in the vacuum pump system as heat sinks permits the evacuation systems to closely track the condenser performance. In certain vacuum pump applications, closed cooling water or service water is used to cool the seal water in the seal water heat exchanger. In such applications, vacuum pumps have to be carefully designed to offer the required evacuation at all suction pressures and corresponding service water temperatures.

### **Pressure Drop in Piping between Condenser and Evacuation System**

There should be a minimum pressure drop in the piping between the condenser and the evacuation package. The length of piping should not exceed 100 feet of equivalent length. It is recommended that the pressure drop in the piping between the condenser and the evacuation system should not exceed 0.05" HgA. Excessive pressure can impact the performance of the evacuation system.

### **Noise**

Under normal operating conditions, noise from the vacuum pump system and steam jet ejector system (with silencer) will rarely exceed 85 dbA at 3 feet in a free field environment. Excessive noise often results from improper flows or abnormal operating conditions for the evacuation system. It should be noted that the noise level guarantees have to be provided by the evacuation package suppliers.

### **Suction Pressures Below 1.0" HgA**

Almost all of the evacuation packages for power plant condensers are designed for suction pressure of 1.0" HgA or higher. The evacuation capacity of the steam jet air ejector system and vacuum pump system decreases as the suction pressure drops below 1.0" HgA. In certain instances, operating pressure below 1.0" HgA may be one of the guarantee points. If such an operating case is anticipated for a short duration then both elements of the ejector system or both vacuum pumps can be pressed into service. If the operating point below 1.0" HgA is a mandatory guarantee point with long duration of operation than a three stage ejector system or a hybrid vacuum pump system would be required.

In a three stage ejector system there are three stages of ejectors. A hybrid vacuum pump consists of a first stage ejector, an inter condenser and a vacuum pump.

### **Oversizing Evacuation Packages**

Sizing vacuum pumps or ejector systems above that specified by HEI standards can cause problems in the long run. Power plant operators often perform leak detection tests and reduce the air leakage into the condenser to levels lower than that specified by HEI standards. Oversizing a liquid ring pump can cause significant operational problems since a pump with substantial excess capacity will evacuate excess water vapor from the main condenser resulting in overheating and cavitation. In the case of an ejector system, the larger ejector system will use excessive motive steam and inter and after condensers may be overloaded.

### **Vent Piping**

Vent piping from the separator tank in the vacuum pump system or from the hogger and after condenser in the ejector system must be routed vertically through the roof or building wall. Valves or reducers must not be included in the vent line. It is recommended that the pressure drop in the vent pipe at maximum flow (hogging) should not exceed 1 psi and the length of the vent pipe should not exceed 60 feet.

## **DESIGN FEATURES APPLICABLE TO STEAM JET AIR EJECTORS**

### **Location of Steam Jet Air Ejector Package**

The inter condenser is designed to operate anywhere between 4.0" HgA to 7.0" HgA. The inter condenser drains into the main condenser hotwell. The main condenser can operate anywhere between 1.0" HgA to 4.0" HgA. The inter condenser drain is equipped with a loop seal or a steam trap. To facilitate condensate drainage from the inter condenser to the main condenser during all operating scenarios, it is recommended that the steam jet air ejector package be placed at an elevation above the high-high water level in the main condenser. If the steam jet air ejector package is placed below the high-high water level in the main condenser than the inter condenser drain must be pumped to the condenser hotwell.

The after condenser typically operates at a pressure 1 or 2 psia above the atmospheric pressure. Due to the large pressure gradient, there are no issues with draining the condensate from the after condenser to the main condenser hotwell.

### **Inter and After Condenser**

Typically the steam jet air ejector package is equipped with a 100% common inter and after condenser. The evacuation capacity of the steam jet air ejector system cannot be doubled by pressing both elements into service. The bottle neck is the 100% common inter and after condenser. If the size of the inter and after condenser is increased from 100% to 200% then both elements can be pressed into service thereby doubling the evacuation capacity of the steam jet air

ejector package. The extra evacuation capacity facilitates removal of air from the condenser during unanticipated excessive air leaks during startup.

### **Range of Condenser Pressure for Satisfactory Ejector Performance**

The steam surface condenser operates under a wide range of loads depending upon the heat duty, circulating water flowrate, circulating water inlet temperature, cleanliness factor and mode of operation (normal or bypass). The range of condenser pressure is typically between 1.0" HgA - 4.0" HgA. The range of condenser pressure must be specified for proper design of the ejector system. The steam jet air ejector may not provide desired evacuation capacity for condenser pressures exceeding the upper limit of the specified pressure range. Higher condenser pressure can be experienced during a transient operational scenario involving high heat duty, lower circulating water flowrate, higher circulating water inlet temperature, excessive air in leakage, fouling of tubes, half tube bundle in service and bypass operation or a combination thereof. In such a scenario both elements can be pressed into service, provided the inter and after condenser has 200% capacity, thereby doubling the air evacuation capacity.

### **Motive Steam Pressure for Steam Jet Air Ejector Package**

The size of the first stage steam jets, second stage steam jets and hogger are dependent on the motive steam pressure and temperature. Motive steam pressure and temperature is typically in the range of 150 psig, 400°F. The ejector can be designed for pressure and temperatures lower or higher than those noted above. It is recommended that motive steam be dry at all times. Motive steam pressures below 50 psia are not recommended. The steam jet air ejectors operate satisfactorily if the motive steam pressure is -0%, +10% of the specified pressure. If necessary, a pressure regulating valve can be included to ensure a constant motive steam pressure for the steam jet air ejectors. Motive steam flow for the first stage ejector, second stage ejector and hogger ejector in the range of 5.0 SCFM to 20.0 SCFM ejector system is included in Table -1. The motive steam flowrates are based on motive steam pressure of 150 psig and temperature of 400°F.

### **Semi-Automated Ejector Systems**

Ejector systems are typically designed for manual operation. Valves must be opened and closed manually to go from hogging to holding and from one element to the other. Motor or pneumatic operated valves can be included in the ejector system to permit operation from DCS. These valves will permit the ejector system to switch from hogging to holding and from one element to the other. The hotwell condensate will be flowing through the tubeside of the inter condenser at all times.

## DESIGN FEATURES APPLICABLE TO VACUUM PUMP SYSTEMS

### Design Suction Pressure for Vacuum Pump System

The vacuum pumps are typically designed for evacuation pressure of 1.0" HgA as required by the HEI standards. The circulating water inlet temperature at the 1.0" HgA operating point is the circulating inlet water temperature required to provide 1.0" HgA condenser pressure for the design heat duty, design circulating water flowrate and condenser design parameters such as heat transfer surface, cleanliness factor and tube geometry. The circulating water inlet temperature at 1.0" HgA has a major impact on the sizing of the vacuum pumps. Lower circulating water inlet temperatures lead to smaller vacuum pumps whereas higher temperatures lead to larger pumps.

The steam-air mixture is cooled in the seal water heat exchanger. The seal water heat exchanger can be a shell & tube heat exchanger or a plate and frame heat exchanger. The motor horsepower, motor brake horsepower during hogging and circulating water flowrate for vacuum pumps in the range of 5.0 SCFM to 20.0 SCFM is included in Table-2. The information in Table-2 is based on a design point of 1.0" HgA with 55.0°F circulating water inlet temperature. It should be noted that a change in the circulating water inlet temperature at 1.0" HgA would substantially alter the contents of the table.

### Inlet Spray System

For evacuation pressures between 1.0" HgA – 2.0" HgA cold water can be sprayed directly into the air vapor stream entering the vacuum pump. The cold spray water condenses some of the vapor in the air-vapor mixture from the condenser thereby reducing the load on the vacuum pump and enhancing its efficiency.

### Low Initial Temperature Difference (ITD)

In certain applications, especially those with once through circulating water applications, the ITD may be relatively low. ITD (initial temperature difference) is the difference between the shellside saturation temperature and the tubeside circulating water inlet temperature. Low ITD makes it difficult to size appropriate vacuum pumps. Furthermore, low ITDs lead to performance problems such as cavitation. The problem can be circumvented with the use of hybrid vacuum pumps consisting of a first stage ejector, an inter condenser and the vacuum pump. The first stage ejector and inter condenser is valved off during hogging operation. During holding, the air-vapor mixture from the condenser is evacuated by the first stage ejector and discharged to the inter condenser. The vent from the inter condenser is directed to the vacuum pump.

## Permanent Loss of Heat in Vacuum Pump Package Applications

In a steam jet air ejector system the steam-air mixture from the condenser mixes with the motive steam in the first stage ejector. The steam-air mixture exiting the first stage jet is condensed in the shell side of the inter condenser. Similarly, the steam-air mixture exiting the second stage ejector is condensed in the shellside of the after condenser. The heat liberated from the condensation is picked up by the hotwell condensate flowing through the tubeside of the inter and after condenser. Therefore, the heat liberated from the condensation of the steam-air mixture is preserved in the cycle and not permanently lost.

In a vacuum pump package, the steam in the steam-air condenses on the seal water. The heated seal water is cooled by circulating water. Therefore, the heat liberated from the cooling of seal water is lost forever.

## COMPARISON BETWEEN STEAM JET AIR EJECTORS AND VACUUM PUMPS

### Vacuum Pumps

#### **Advantages:**

- Typically 2x100% vacuum pump with motors and auxiliaries are supplied. All components are pre-piped, pre-valved, pre-wired and mounted on a common skid.
- Do not need steam to start the vacuum pumps.
- Full automation. Can operate remotely from DCS.
- During startup (hogging) remotely deploy both pumps into service.
- During normal operation (holding) keep one pump in operation.

#### **Disadvantages:**

- Pumps and motors have rotating parts and therefore need maintenance.
- The seal water heat exchanger for the pump uses circulating water. The seal water heat exchanger must have the tubes/tubesheet (or plate and frame) material compatible to the main condenser.
- Vacuum pumps are about 40% more expensive than a manually operated steam jet air ejector system.
- In the seal water heat exchanger, the heated seal water is cooled by the circulating water. The heat rejected to the circulating water is lost forever.
- The evacuation capacity of the vacuum pumps decreases with increasing circulating water inlet temperature and decreasing loads. All potential low load and high circulating water inlet temperature cases must be considered and accounted for to make sure that the vacuum pump provides the adequate evacuation capacity under all operating conditions.

## Steam Jet Air Ejector Packages

### **Advantages:**

- Typically two stage twin element steam jet air ejector with a common inter and after condenser and a hogger are provided. All components are pre-piped and pre-valved and mounted on a common skid.
- There are no rotating parts thereby eliminating maintenance.
- Manual ejector package is 40% less expensive than vacuum pump package.
- Condensate from the condenser hotwell is pumped by the condensate pumps and then directed through the tubeside of the inter and after condenser. The steam in the steam-air mixture from the condenser is condensed on the shellside of the inter and after condenser. This heat is transferred to the tubeside condensate. Thus, the heat is preserved in the cycle (and not lost to the circulating water as in the vacuum pump application).
- Condensate flows through the tubeside of inter and after condenser. The inter and after condensers are equipped with 304 stainless steel tubes and tubesheets.
- The ejector package can be automated such that the holding and hogging ejectors can be operated remotely from the DCS.

### **Disadvantages:**

- Need steam to operate the hogger during startup and holding jets during normal operation.
- In a manual ejector system, valves have to be turned on and shut off manually to switch from hogging to holding mode and to switch from one element to the other. This disadvantage can be circumvented by using automated ejector system.
- Need to account for pressure drop of condensate through inter and after condenser. Have to be careful about the minimum condensate flow through inter and after condenser. It is important to determine the

minimum condensate flow and then make sure that the ejector package can work with the minimum condensate flow through inter and after condenser.

- Ejector package must be placed above the condenser hotwell to facilitate drainage of inter condenser drain to the condenser hotwell.

## CONCLUSION

Either vacuum pumps or steam jet air ejector systems can be used to evacuate the air from the condenser. The selection of the evacuation system depends on the availability of motive steam during startup and normal operation, cost of parasitic load and preferences of the end user. The advantages and disadvantages of the two systems and other design and operational issues listed in the paper should be carefully considered in the selection process.

## ACKNOWLEDGMENT

The contribution of contents in Tables 1 & 2 and Figures 1-3 from Paul Lynch of Mercury Vacuum Technologies, Parsippany, NJ, is sincerely acknowledged.

## REFERENCES

- [1] Heat Exchange Institute: Standards for Steam Surface Condensers, Eleventh Edition
- [2] Heat Exchange Institute: Standards for Air Cooled Condensers, First Edition
- [3] Heat Exchange Institute: Performance Standards for Liquid Ring Vacuum Pumps
- [4] Heat Exchange Institute: Standards for Steam Jet Vacuum Systems

**TABLE-1-TYPICAL STEAM JET AIR EJECTOR DESIGN DATA**

Evacuation Capacity Holding/Hogging capacity, SCFM	Condensate flow through IC/AC, gpm	Steam Consumption first stage jet, lbs/hr (Note 1)	Steam consumption second stage jet, lbs/hr (Note 1)	Steam consumption Hogger, lbs/hr (Note 1)
5.0/50.0 SCFM	150.0	185	185	450
7.5/100.0 SCFM	350.0	290	295	890
10.0/200.0 SCFM	750.0	390	395	1750
12.5/350.0 SCFM	1500.0	460	460	3120
15.0/700.0 SCFM	3,000.0	580	585	6110
17.5/1050.0 SCFM	5,000.0	660	675	9460
20.0/1400.0 SCFM	7,000.0	760	760	12,460

**NOTE 1: THE MOTIVE STEAM REQUIREMENT FOR THE FIRST STAGE, SECOND STAGE AND THE HOGGER FOR VARIOUS EJECTOR SIZES ARE INCLUDED IN THE TABLE ABOVE. THE STEAM FLOW IS BASED ON A MOTIVE STEAM CONDITION OF 150 PSIG/400°F.**

**TABLE-2-TYPICAL VACUUM PUMP DESIGN DATA**

Evacuation Capacity Holding/Hogging capacity, SCFM	Cond. Pressure " HgA	Cooling water Inlet temp, °F	Motor HP	Motor Bhp during hogging	Circulating water flowrate for plate and frame HX, gpm
5.0/50.0 SCFM	1.0	55.0	40	28	60
7.5/100.0 SCFM	1.0	55.0	50	38	70
10.0/200.0 SCFM	1.0	55.0	75	67	80
12.5/350.0 SCFM	1.0	55.0	100	72	90
15.0/700.0 SCFM	1.0	55.0	100	75	110
17.5/1050.0 SCFM	1.0	55.0	100	79	120
20.0/1400.0 SCFM	1.0	55.0	125	90	140

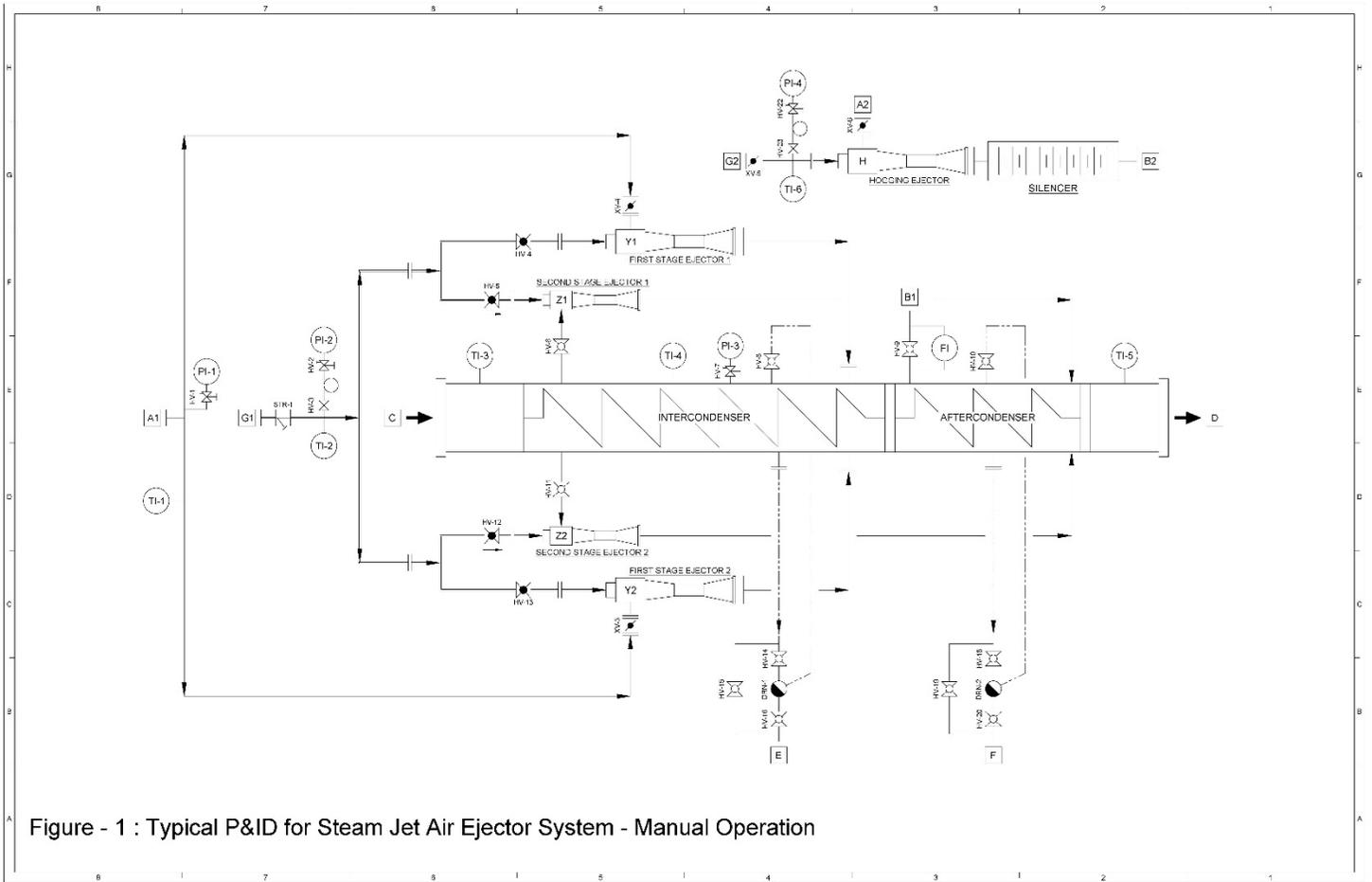


Figure - 1 : Typical P&ID for Steam Jet Air Ejector System - Manual Operation

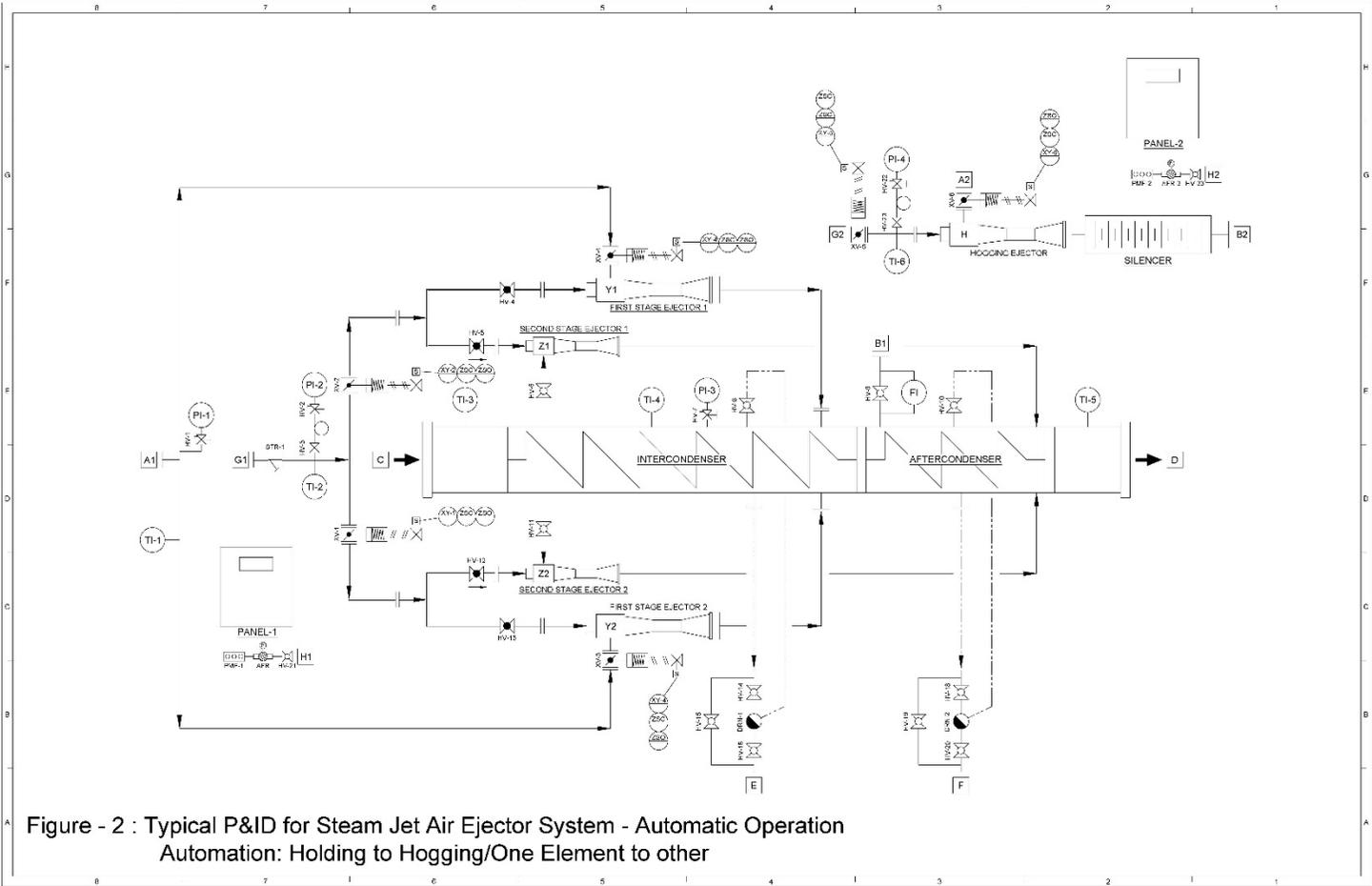


Figure - 2 : Typical P&ID for Steam Jet Air Ejector System - Automatic Operation  
Automation: Holding to Hogging/One Element to other

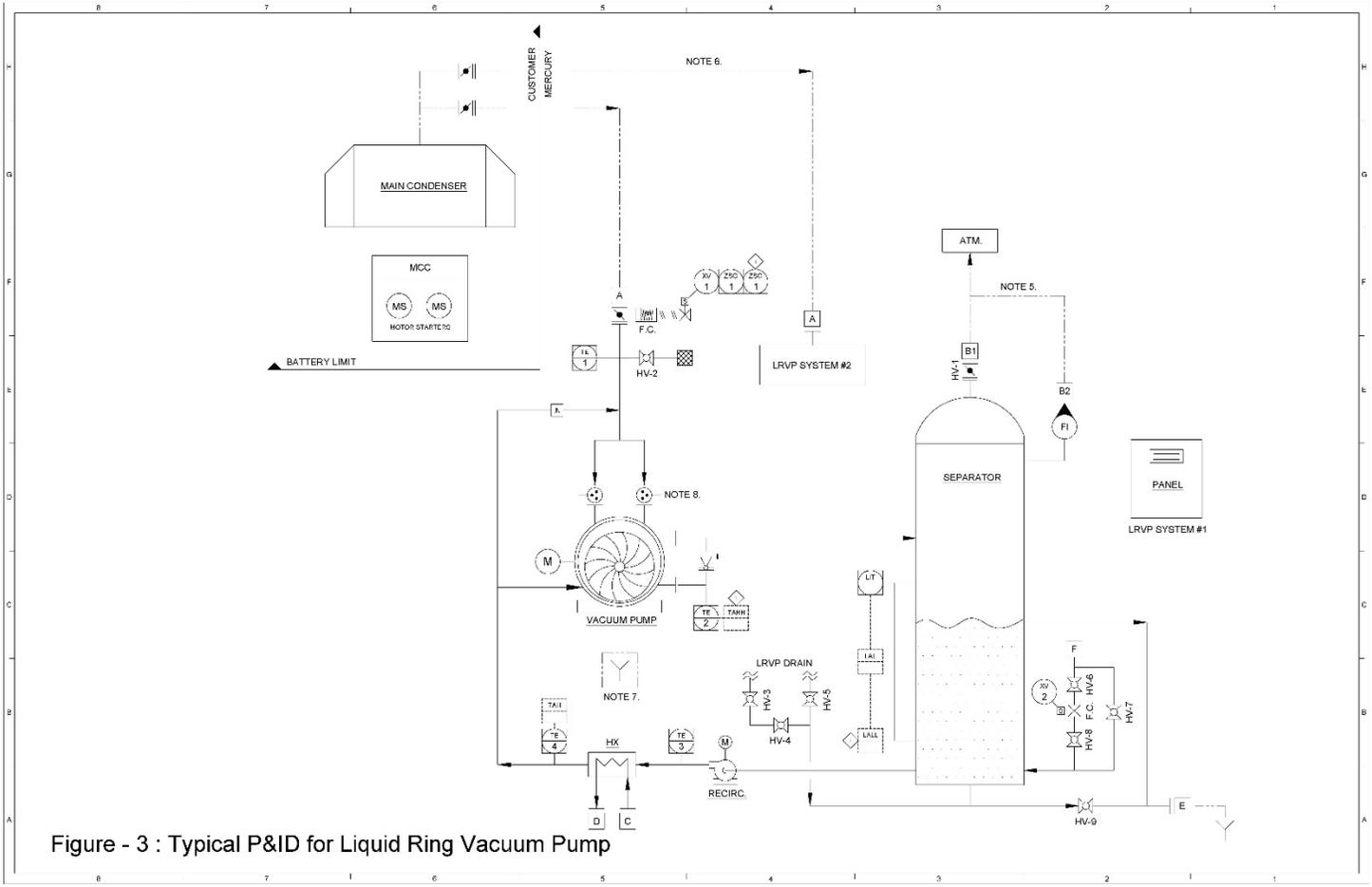


Figure - 3 : Typical P&ID for Liquid Ring Vacuum Pump