A Novel Use of HYSYS to Design an Industrial Refrigeration System

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Introduction

Industrial refrigeration systems such as those present in an ethylene plant or an ammonia plant are designed based on the demand of refrigerant in the process. Once the duties of the heat exchangers and the temperatures of the refrigerant are specified, the refrigeration system consisting of compressors, condensers and flash drums can be designed. Process simulators such as Provision or Aspen can be used to design the refrigeration system by using feed-forward or feed-back controllers to determine required refrigerant flow rates and the resulting compressor capacities. This technique often results in many control loops, each requiring many iterations to converge. This paper is the result of a senior project (1) undertaken by a chemical engineering senior at Cal Poly, Pomona. It describes how HYSYS has been used successfully to design a refrigeration system with 4 compressors, 13 heat exchangers and 4 flash drums without resorting to numerous control and recycle loops. The intent of this paper is not to provide a rigorous comparison between simulators, but to focus on a special technique used for solving industrial refrigeration design problems. It is expected that the same technique can be applied to other utility systems.

What is an industrial refrigeration system?

An ethylene manufacturing process usually consists of a hot section and a cold section. The primary equipment in the hot section is the pyrolysis furnace in which hydrocarbons are cracked at temperatures in excess of 1000^{o} F to form ethylene and a slate of byproducts including methane, ethane, propylene, C4's and C5 and heavier hydrocarbons. The cold section consists of a series of distillation columns, flash drums and exchangers which separate pure ethylene from the byproducts. The cold section operates under cryogenic conditions with temperatures ranging from -160^{o} F to -25^{o} F. Refrigerants, usually ethylene and/or propylene of several temperature levels, are used as coolants in exchangers and condensers.

Figure (1) shows the basic elements of a single level ethylene refrigeration system. Ethylene vapor is compressed in a compressor C1 from pressure P_1 to P_2 while temperature rises from T1 to T2. The compressed ethylene is cooled to temperature T3 and condensed to liquid in an exchanger E1. The liquid ethylene is expanded adiabatically in an expansion valve V1 to P3 while the temperature is further lowered to T4 and the the liquid is partially vaporized. The vapor is separated in a flash drum from the liquid which is used as a refrigerant in a process exchanger E2. The process stream is cooled and the liquid refrigerant absorbs the process duty Q and is vaporized. The vapor ethylene returns to the suction head of the compressor hence completing the cycle. The size of the compressor C1, exchanger E1, expansion valve V1 and the flash drum F1 depends on the temperature level of the refrigerant and the process duty Q.

A multi-level industrial refrigeration system is comprised of a combination of several single level refrigeration system. Figure (2) shows a four-level ethylene refrigeration system which has four refrigeration loops each consisting of a compressor, a flash drum and several process exchangers demanding refrigerants. Let us follow this process by starting with Stream 1 which is the outlet stream from the fourth stage compressor and has the highest pressure in the system. This stream passes through a series of heat exchangers until the vapor is completely condensed. Part of the liquid from the last exchanger E-103 passes through an expansion valve in which the liquid ethylene is further cooled and partially vaporized creating the first level refrigerant having the highest temperature. The remaining liquid from the exchanger E-103 is further expanded in a series of expansion valves creating three other levels of refrigerants of successively low temperatures. Four flash drums are required to separate the the mixed phase products into vapor and liquid refrigerant. There are a total of thirteen heat exchangers nine of which have demands for refrigerants of different temperature levels. The other five are process heat exchangers which are integrated into the refrigeration system and used for cooling and condensing the compressed ethylene to liquid.

Design of An Industrial Refrigeration System

Once the temperature levels of the refrigerant and duties of the heat exchangers requiring refrigerant have been decided, the design of the refrigeration system can proceed by contructing a process flow diagram (PFD) such as figure (2) The design of the system involves the generation of the material and energy balances for the process. Calculation of compressor horsepower, duties of coolers and condensers and sizing of the flash drum follow. Like other manufacturing processes, material and energy balances can be generated through the use of a process simulator. However, there are two basic differences between a manufacturing process and a refrigeration process. First, to simulate a manufacturing process on a process simulator one can always start with feeds of known flow rates and the process simulator calculates the flow rates of products. In a refrigeration system, the refrigerant flow rate depends on the cooling demand of the process. Second, a manufacturing processs has feeds and products while a refrigeration system has neither feeds nor products. The refrigerant simply re-circulates itself in many recycle loops. Material flows within a refrigeration system have to be determined by duty demands.

Material and Energy Balances Using Process Simulators

In determining material and energy balances around a unit operation, most process simulators calculate the product condition from the given feed condition. For instance, the condition of the refrigerant after an exchanger can be determined only if the flow rate and condition of the refrigerant before the heat exchanger and the required duty are specified. In order for the exchanger to be effective, all the refrigerant passing through the exchanger must be vaporized to become a saturated vapor and the flow rate of the refrigerant must be predetermined.

There are two ways of determining this flow rate. The first method is to calculate the flow rate by dividing the specified duty by the heat of vaporization. In the simulation environment, this means placing a calculator before a splitter and an exchanger. A calculator is a user-supplied procedure to perform a calculation using any process variable. The procedure is usually written in a Fortran-like language specific to each simulator. The arrangement is shown in Figure (3). The calculator C1 calculates flow rate F1'. In the splitter S1, Stream F1 is set equal to F1' and F2 is calculated by difference. Every heat exchanger requiring refrigerant has to be accompanied by a calculator and a splitter.

The second method is depicted in Figure (4). A feedback controller is used to vary the flow rate F1 in order meet the specified duty of the heat exchanger. Again, every refrigerant heat exchanager has to be accompanied by a splitter and a feed back controller.

Method 1 predetermines the flow rate by a feed-forward action and converges easily, usually within five trials. Method 2 is based on a feedback action. When there are more than 15 controllers, convergence could be time-consuming. The advantage of Method 2 is that it does not require any programming while Method 1 needs familiarity with the programming language and some programming effort.

Material and Energy Balances Using HYSYS

HYSYS , a graphic oriented simulator, is a product developed by Hyprotech to replace HYSIM. A comparison between HYSYS and HYSIM or HYSYS and other simulators is beyond the scope of this paper. It is generally known that HYSYS has a unusual feature which calculates the rate of cooling water in an exchanger if the duty is specified and the inlet and outlet water temperatures are also specified. For example, if cooling water is available at 75^{O} F and the outlet temperature is specified at 100^{O} F, HYSYS calculates the flow rate of the water. This feature can be applied to a refrigerant exchanger in which the product refrigerant is specified as saturated vapor and the refrigerant flow rate can be calculated from the specified duty. This is precisely what the design of an industrial refrigeration system entails. In an industrial system in which there are many exchangers requiring refrigerants at many temperature levels, the simulation of such as a system is much simplified if the PFD contains only real equipment and the only data that need to be entered are the specifications of the refrigerant exchangers.

The elimination of controllers or calculators also makes the simulation much easier from the numerical convergence standpoint. A process engineer or a student can design this complex system without resorting to a calculator language or multiple control loops The PFD consists of only real equipment other than a cluster of non-equipment items such as controllers and calculators.

Design of an Ethylene Refrigeration System

The industrial refrigeration system shown in Figure (2) provides four levels of ethylene refrigerant. There are eight heat exchangers requiring refrigerant, one exchanger condensing ethylene vapor to liquid and four coolers using process streams to cool the compressed ethylene. There is a four-stage compressor which compresses the ethylene vapor from 16 psia to 283 psia. The temperature of the refrigerant ranges from -152 F to -22 F. There are four flash drums which serve two purposes. First, they are used for separating mixed-phase products expansion valve into vapor and liquid. Second, they serve as collection vessels for the refrigerant vapor exiting refrigerant exchangers.

The outlet streams of the two condensers E101 and E102 are specified as saturated liquid and duties for these heat exchangers are calculated. In this manner, the condensers are designed such that they deliver sufficient duty to condense all refrigerant vapor to liquid.

To facilitate convergence, initial estimates of two streams S1 and S2 are provided. The stream S3 calculated by HYSYS from exchanger duties of E11 and E12, is considered an external feed stream. The product S4, which is the same stream as S3, will equal S4 when the system converges. The simulation executes very fast generally converging in less than 10 seconds.

To demonstrate the flexibility of the system, we change duty specs first on one exchanger, then on several exchangers simultaneously. The system responds appropriately by re-calculating the correct flow rates and compressor horsepowers.

Conclusion

HYSYS is an effective tool for conducting a process design for an industrial refrigeration system.. A process engineer or a student first constructs a PFD showing all necessary real equipment . To design the system, all he/she needs to do is to specify that refrigerant exchanger outlet condition to be saturated vapor and required duties.   HYSYS will calculate the necessary flows and compressor duties . Once the model is constructed, it can be used to study the effect of changing refrigerant duty requirements. The process scheme can also be re-configured easily to increase or decrease the number of refrigerant levels or to change temperatures of these levels. All this is done without the complexity of controllers and calculators. The simulation of the refrigeration executes very fast, generally converging in less than 10 seconds.

Bibliographic Information

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Biographical Information

K. HING PANG Joined Cal Poly, Pomona in 1994 as an Associate Professor after working in industry for 26 years Before joining Cal Poly, he spent 17 years with Brown & Root and C F Braun, four years with Simulation Sciences and 5 years with Inco. His recent research interest is in computer-aided process engineering. He holds a BASc degree from University of British Columbia and a M Eng and A PhD degree from McMaster University.

FIGURE (1) A SINGLE-LEVEL ETHYLENE REFRIGERATION SYSTEM

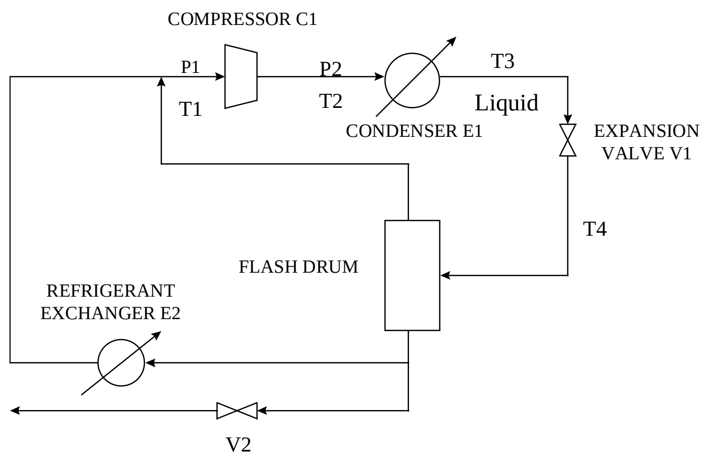

FIGURE (3) USE CALCULATOR TO CALCULATE FLOW RATE

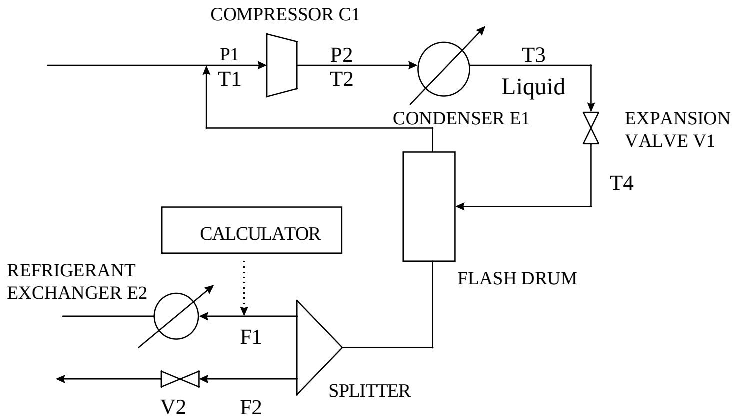

FIGURE (4) USE CONTROLLER TO CALCULATE FLOW RATE