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STEAM ATMOSPHERE DRYING CONCEPTS USING STEAM EXHAUST RECOMPRESSION

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ABSTRACT

In the United States, industrial drying accounts for approximately 1.5 quads of energy use per year. Annual industrial dryer expenditures are estimated to be in the $500 million range. Clearly, industrial drying is a significant energy and monetary expense for the United States industrial complex. For the thermal drying processes in which water is removed via evaporation from the feedstock, attempts have been made to reduce the consumption of energy using exhaust waste heat recovery techniques, improved dryer designs, or even the deployment of advanced mechanical dewatering techniques. Despite these efforts, it is obvious that a large amount of thermal energy is often still lost if the latent heat of evaporation from the evaporated water cannot be recovered and/or in some way be utilized as direct heat input into the dryer.

Under a contract with the Department of Energy, Tecogen Inc. is conducting research and development on an industrial drying concept. The concept utilizes a directly or indirectly superheated steam cycle atmosphere with exhaust steam recompression to recover the latent heat in the exhaust that would otherwise be lost. This approach has the potential to save 55 percent of the energy required by a conventional air dryer. Other advantages to the industrial dryer user include:

- A 35-percent reduction in the yearly cost per kg_{evap} to dry wet feedstock
- Reduced airborne emissions of both feedstock effluent and combustion exhaust products
- Reduced dry dust fire/explosion risks
- Hot product not exposed to oxygen; product quality is enhanced
- Constant rate drying in steam atmosphere
- Reduced dryer size and cost
- Reduced dryer heat losses due to lower dryer inlet temperatures

Based on these advantages Tecogen has projected that the steam atmosphere drying system is most suitable as a replacement technology for state-of-the-art spray, flash, and fluidized bed drying systems. Such systems are utilized in the food and kindred products (SIC 20); rubber products (SIC 30); chemical and allied products (SIC 28); stone, clay, and glass (SIC 32); textiles (SIC 22); and pulp and paper (SIC 26) industrial sectors.

REVIEW OF PRIOR SUPERHEATED STEAM DRYING WORK

A literature search conducted at the beginning of Phase I of the program identified 18 projects in which superheated steam had been considered or used for drying. Although one program dates back to 1920, the majority of the work was done in the 1980's. A summary of this literature search is given in the Phase I final report (DiBella, F.A., Doyle, E.F., Becker, F.E., and Lang, R., "Research and Development of Industrial Drying Concepts Using a Superheated Steam Atmosphere with Exhaust Recompression," Phase I Final Report, Prepared for U.S. Department of Energy, January 1991). The first task of the Phase I work identified the names of the researchers and references dryer configurations, feedstocks tested, level of development (analysis, laboratory testing, pilot plant, or commercial installation), successes, problems, and stated conclusions.

Most of the recent research on superheated steam drying has been conducted outside of the United States, particularly in Europe, Canada, Australia, and South Africa. While some of the programs considered steam recompression, only two have proceeded to a pilot plant, and none are commercially available either inside or outside the U.S. Several pilot plants have been built and use superheated steam <u>without</u> steam recompression. The types of dryers investigated have been quite varied and have included spray, flash, fluidized bed, yankee, tray, kiln, convective, and film. Equally varied have been the products dried. They include milk, whey, cabbage, hay, soybean flakes, soy sauce cake, sugar beet pulp, coffee nutrient, coffee slip, paracetomal, bone protein, detergent whitener, clay, tissue paper, pulp, timber, textiles, alumina, activated carbon pellets, coal, sodium nitrate, and cellulose acetate. The successes, problems, and conclusions from this prior work provide a valuable guide in our selection of applications that offer a high probability of commercial success. It is interesting to note the encouraging successes in drying both food and non-organic materials using steam as the drying medium.

The literature also identified an important limitation that must be considered when superheated steam is substituted for air in conventional flash or spray dryers. For example, particles travel faster and have longer trajectories in steam because steam is less dense than air. If the dryer vessel configuration design is not modified, the drying chamber would have to be made larger to obtain the same drying capacity with superheated steam as with air.

Tecogen's study of the state-of-the-art industrial air and prototype steam atmosphere dryers revealed several important results.

1. The superheated steam atmosphere drying concept with steam exhaust recompression can compete best against the state-of-the-art spray, flash, and fluidized-bed types of dryers.

2. Spray, flash, and fluidized bed dryers annually use 0.667 quads of energy, which is 55 percent of the total drying energy consumed in the United States.

3. The typical weighted efficiency for these types of dryers is 62 percent.

4. There are approximately 10,000 spray, flash, and fluid bed dryers in use in the United States, with a nominal size of 2,730 to 4,550 kg/hr of water evaporated.

5. The capital costs for these types of dryers are high, and competitive systems would be welcome.

6. Only spray and flash dryers can be used for the many and varied pumpable (slurried) feedstocks.

7. A 10-percent penetration of the market for spray, flash, and fluidized bed dryers by superheated steam dryers with exhaust recompression would save 11.6 x 10^{12} kJ/yr.

8. Successes with drying food (i.e., temperature sensitive) as well as non-organic (i.e., temperature insensitive) materials have been documented in the literature.

TECOGEN'S DIRECT STEAM ATMOSPHERE DRYER (DSAD) WITH EXHAUST STEAM RECOMPRESSION

Drying in a superheated steam atmosphere with exhaust steam recompression offers a better approach for reducing the energy requirements in many applications where air is used now. In addition, superheated steam has several other potential advantages as a drying medium. It does not subject sensitive products to oxidation damage, and since no flammable materials are involved, there is no risk of explosion. It provides a high humidity environment, which is required in some specialized applications.

The first of two proposed steam atmosphere drying cycles, a direct steam dryer with exhaust steam recompression concept, is illustrated in Figure 1. Superheated steam is circulated by a fan through the heat exchangers and Tecogen's novel drying chamber. In the drying chamber, moisture is thermally driven from the product and carried off by the recirculating superheated steam. A portion of the superheated steam exhausted from the drying chamber (equal to the amount of moisture removed) is taken off and compressed. The compressed steam then gives up its heat of compression and latent heat of evaporation in the heat exchanger. This is the primary, and possibly only, source of heat for the drying process. If economics dictate, an auxiliary fossil-fuel-fired heat may be provided to reduce the size and cost of the steam recompression system. The liquid condensed in the heat exchanger passes through an expansion valve, is used for preheating the feedstock, and is then vented.

One of the most innovative features of the proposed concept is its use of a unique design for the steam dryer chamber. Tecogen and a leading manufacturer of industrial dryers are completing the design details of this drying vessel as of this writing. High heat transfer and drying rates are achieved by intimate contact of the superheated steam with the particles being dried. Through high internal recirculation rates, the residence time of the particles in the drying atmosphere is increased substantially, resulting in a decrease in the overall dryer vessel volume and an increase in the effective overall heat transfer coefficients for the dryer.

A computer program was written to model the steam atmosphere dryer system using the constants shown above, and an extensive parametric analysis was performed. It was found that the system pressure drop, the compressor pressure ratio, and the dryer inlet temperature were the three principal design parameters that most significantly affected the steam dryer system's energy requirements and system cost.

Tecogen's thermodynamic analysis of the steam atmosphere dryer and steam recompression system used the following system component efficiencies and operating parameters:

Fan/Blower Pressure Rise	10 to 40 in. wc
Fan/Blower Efficiency	0.60
Elec. Motor Efficiency	0.95
Auxiliary Boiler Efficiency	0.85
Electric to Thermal Conversion Efficiency	0.3 (3334 watts/kWe)
Dryer Ambient Inlet Temperature and R.H.	21.1°C; 50%
Feedstock Inlet Water Content	50% (D.B.)
Feedstock Outlet Water Content	5% (D.B.)
Auxiliary Steam Boiler Thermal Efficiency	85%

Feedstock Preheated Temperature (Maximum)	60°C
Steam Compressor Thermal Efficiency	0.70
Heat Transfer Loss (Steam Dryer and Steam Reboiler)	1.5% each
Reboiler Pinch Point	4.4°C
Reboiler Subcool Temperature Drop	14°C
Steam Dryer Outlet Temperature	104.4°C
Compressor Pressure Ratio*	2.0 to 6.0
Dryer Inlet Temperature*	115.6°C to 315.6°C

*Principal design parameter used in parametric analysis.

The total energy (reported as kJ per kg of water evaporated from the feedstock) is the sum of the energies required to drive the steam compressor and the steam circulating fan/blower added to the auxiliary heat needed to sensibly heat the recirculation steam flow to the desired steam dryer inlet temperature.

The thermodynamic advantage of using a steam compressor is comparable to using a heat pump between a low-temperature reservoir (i.e., the dryer exhaust stream) and a higher-temperature reservoir (i.e., the dryer inlet stream). The coefficient of performance (COP) or heat pump efficiency for this heat pumping action is defined as the ratio of heat delivered to the dryer recirculating steam to the work of compression required by the steam compressor. Thus, high COP's are desirable, but as will be seen, they can be achieved only if low (less than 149°C) steam dryer inlet temperatures are used.

The performance of a direct steam atmosphere dryer with recompression is summarized in Figure 2. The minimum heat requirements can be observed to be 2356 kJ/kg_{evap} at approximately 138°C dryer inlet temperatures. This optimum performance state point requires no additional heat input from the auxiliary heater. The energy savings between this state point and the comparable air-dryer operating condition is approximately 40 percent at an air-dryer stack temperature of 65.6°C, and approximately 85 percent at an air-dryer stack temperature of 260°C (assuming air recirculation ratio equals 0 and humidity equals 0.4). Clearly, this is a substantial performance improvement.

In order to achieve the locus of state points shown in Figure 2, the steam compressor pressure ratio was varied until no auxiliary heat input was required to attain the dryer inlet temperature shown. The steam compressor's pressure ratio, and hence the steam recompression system's COP, can consequently be observed to change as the desired dryer steam inlet temperature increases from 115.6°C to 176.7°C. Figure 3 shows the increase in steam compressor ratio and the subsequent decrease in the system's COP.

Although there is a clear minimum heat requirement identified in Figure 2, the performance of the steam dryer cycle at the low dryer inlet temperatures requires that a large amount of recirculated steam flow rate be maintained through the steam dryer. Consequently, the fan/blower power requirements for the steam cycle are significant and are comparable to those of the steam compressor. For example, at the 135°C (minimum) state point operating condition, the fan/blower and steam compressor would each require a 180-kW electric motor drive for 2272 kg/hr of evaporation duty.

The volume of steam flowing through the dryer is found to be very high at dryer inlet temperatures below 204°C when compared with the flow rate of air in standard air dryers. This implies that the size of the dryer system piping and components would need to be made larger if equivalent system pressure drops were to be maintained. Figure 4 displays the significantly greater volume flow rate of steam required at 93°C to 204°C as compared with air volume requirements in dryers that typically operate at temperatures above 260°C. It is important therefore to design the steam dryer system with lower volume flow rates; i.e., reduce the steam recirculation ratio (R).

The steam recirculation rate (R) (the ratio of recirculated steam to evaporated feedstock water) can be <u>decreased</u> by <u>increasing</u> the steam dryer inlet temperature. However, as can be observed in Figure 3, the steam compressor pressure ratio must be increased with a subsequent reduction in the steam compressor's COP. Thus, although an increase in dryer inlet temperature results in a decrease in the recirculation rate, the use of auxiliary heat input from a fuel-fired steam heater would be required. This results in an increase in the amount of heat required to evaporate 1 kg of water from the feedstock.

In the event that higher steam inlet dryer temperatures are desired and auxiliary heat input is used to increase the steam temperatures exiting the steam reboiler, the use of steam as the drying medium still provides an advantage over the conventional air-dryer system, in that a maximum heat input limit is reached ($Q_{max,steam}$) that is still 7 to 42 percent lower in energy requirements than the best air-based dryer performance. For example, as shown in Figure 5, the need for higher steam dryer inlet temperatures results in the locus of state points (with the same compressor pressure ratio as originally displayed in Figure 2) to equilibrate to a steady state and maximum heat input of approximately 3064 kJ/kg_{evap} as auxiliary heat input to the steam is increased. Shown in Figure 5 are six curves, each the locus of state points originally displayed in Figure 2. However, now each curve displays an increase of superheating steam temperature of 11°C, 28°C, 50°C, 111°C, and 167°C higher than the original optimum steam cycle reboiler discharge temperatures shown in Figure 2. The effect observed in Figure 5 is the transition from a system that has 100 percent of the dryer recirculation steam heated with a steam heat pump to one that has 90 to 95 percent of its heating derived from the auxiliary heating system. For such a system, the fan/blower and steam compressor power requirements are considerably lower, requiring as little as 30 kW for the blower and steam compressor for 2273 kg of evaporation duty/hr.

INDIRECT STEAM ATMOSPHERE DRYING SYSTEM (ISAD) WITH EXHAUST STEAM RECOMPRESSION

An alternative means of reducing the steam recirculation flow rate and thereby reducing the steam fan power parasitic is to use an indirect steam atmosphere drying system as outlined in Figure 6. In this alternative steam dryer the feedstock drying is produced by conduction heat transfer from the dryer's steam-heated jacket in addition to convection drying from the recirculated or transport steam medium.

A thermodynamic analysis of this system reveals that the very low recirculation (transport) steam flow rate requirements cause this system to be less sensitive to the dryer's fan power parasitic. In fact, the very low recirculation flow rate allows the overall system pressure drop to increase without critically increasing the power required for the steam fan. The heat input requirements for the indirect steam atmosphere dryer are displayed in Figure 2 and can be compared with the previously quoted performance of the direct steam atmosphere dryer system. Thus it can be observed that the heat input requirement for an indirectly heated steam system (i.e., one that utilizes a steam jacket) with a 40-in. water system pressure drop results in a 20-percent decrease in heat requirements when compared with the direct steam atmosphere dryer with a 10-in. water overall system pressure drop.

The low recirculation flow rate (R) is a net result of providing most of the dryer's heat requirements via conduction heat transfer between the dryer's jacketed wall and the feedstock's water-laden particle. The amount of heat required to preheat, vaporize, and superheat the water entrained in the feedstock is fixed at approximately 2600 kJ/kg_{evap} whether the heating is to be done with the DSAD or the ISAD system. If a large portion of this heating is available via conduction, then less heat will be needed from the superheated transport steam medium. If less heat is required from the transport steam its flow rate through the dryer can be reduced. The net result is a decrease in the recirculation flow rate ratio (R) and thus a decrease in the impact of the system's pressure drop on steam fan parasitics. It must be noted, however, that the proportion of wall conduction heating and transport steam heating that is possible with Tecogen's steam dryer vessel will depend on the magnitudes of the heat transfer coefficients as well as the vessel's internal surface area. The overall system cycle performance results shown in Figure 2 depict the limits of heating requirements for the DSAD and ISAD.

The thermodynamic analysis conducted for the ISAD revealed that 90 percent of the heating requirements of the feedstock can be met by the steam compressor's steam output. The direct consequence of this is a drastic reduction (by almost 10:1) in the dryer's recirculation ratio (R) when compared with a DSAD system.

With a lower recirculation ratio the dryer system's overall volume flow rate is reduced. Consequently, the fan power parasitic is reduced, which ultimately provides a more efficient steam atmosphere drying system. In fact, the lower fan parasitic in the ISAD system results in the constant need for an auxiliary steam heater for the transport steam. Unlike the DSAD's system, the ISAD's fan power (i.e., heat) input to the system is not sufficient to avoid the use of an auxiliary steam heater. This is an advantage for the ISAD system because the thermodynamic irreversibility of the heat input into the transport steam is reduced if it is performed via heat transfer rather than by producing heat energy input from the mechanical energy required to rotate the steam fan.

The ISAD does have a small drawback in that it requires a slightly larger steam compressor discharge pressure. This also results in a slight decrease in the system COP when compared to the DSAD system. These consequences, however, are minor compared to the significant improvements in energy requirements. Compared to the best air standard system, in which energy heat inputs may range from 3249 to 3946 kJ/kg, the ISAD system requires an energy input of only 1450 to 1860 kJ/kg_{evap} for an energy savings of from 43 to 63 percent.

Two steam dryer system configurations were identified and studied in detail. Each of these systems provides a significant improvement in energy input requirements when compared with the standard air dryer system, i.e., 43 to 63 percent. The indirect steam atmosphere dryer (ISAD) requires lower energy inputs than the direct steam atmosphere dryer (DSAD) system. However, its requirement for conduction as well as convection heat transfer makes it more complicated than the simpler DSAD design. A study of the conduction heat transfer mechanism of the ISAD system is required. For example, the conduction heat transfer coefficients must be measured in a laboratory test for the new dryer. Also, the use of extended surface within the dryer to promote the conduction heat transfer must also be considered. Both of these tasks will be conducted in Phase II of the project.

HOT TEST EXPERIMENTATION OF TECOGEN'S STEAM ATMOSPHERE DRYER VESSEL

As part of the DOE Phase I work task, a steam atmosphere drying hot test laboratory apparatus was designed and assembled specifically for the hot testing of a bench-scale model of Tecogen's steam atmosphere dryer. The purpose of these tests was to dry a slurry mixture of feedstock and water to its constituent powder and observe the effects of steam drying on the powder properties and to characterize the heat transfer capability of the dryer, measuring heat transfer coefficients. Tecogen's hot test steam atmosphere drying laboratory apparatus is shown in Figure 7 consisting of the steam dryer, facility boiler, and cyclone particle separator.

The steam atmosphere drying facility generates high-pressure saturated steam at 960 kPa which can be immediately flashed to atmospheric pressure and hence to a superheated temperature. Typically, 170 to 182 kg/hr of steam at 140° to 143°C could be maintained for use by the bench-scale IRIS-type steam dryer. There was some difficulty in maintaining constant maximum flow rate through the dryer. Approximately 5 to 8 percent of this steam was used in a specially designed <u>steam atomizer nozzle</u> that would atomize the liquid feedstock slurry that was to be tested. Both the main dryer steam flow rate and the steam injector flow rate were individually measured using two ASME-designed steam orifices. The pressure drops were measured by a Foxboro-series pressure transducer.

The steam atmosphere dryer vessel used the steam to vaporize the water-laden atomized feedstock. Liquid (slurry) drains were installed into the bottom of the steam dryer. Drainage from the steam dryer was collected in a 100-ml beaker, and its contents were recorded after each test run. This drainage represented slurry that could not be dried (for whatever reason) by the steam dryer and was not carried out of the dryer in the form of wet steam and dried particles. The dried feedstock particles leaving the steam dryer were separated from the transport steam by the cyclone particle separator. The separator included a collection box at its bottom where dried feedstock collected and could be removed. Three heater tapes (each at 600 watts) were installed on the walls of the dryer vessel and cyclone particle separator. The cyclone heater remained in operation in all the tests, but the IRIS dryer heater tape was in use in only a limited number of the tests.

The wall temperatures of the dryer and cyclone were monitored very closely during each hot test. In all of the testing, temperatures were found to be hotter than 100°C, and usually the walls were at a temperature of 118°C <u>without</u> requiring wall heaters. The wall temperatures of the external recirculation line were typically 116°C and clearly indicated that recirculation was present in this line. The only exception to these high temperatures was found on the walls near where the slurry was injected. Those wall temperatures were typically 100°C.

The entire steam atmosphere apparatus was insulated with 10 cm-thick Fiberfrax insulation. This insulation was adequate to maintain a minimum of heat loss through the system. The heat loss was estimated by measuring the steady-state temperatures into and out of the steam dryer before slurry was injected into the dryer. An average of 640 watts heat loss was measured, and this value was used in the data reduction computer program for each test point.

TESTING PROCEDURE

A typical testing procedure consisted of the following:

(1) The entire steam atmosphere dryer test apparatus was heated with the facility boiler steam and was allowed to reach steady-state temperatures.

(2) A batch of pumpable slurry mixture was prepared. A 6.8 kg, 50-percent (dry basis) sample of a water and feedstock mixture was typically enough for a 1-hour to 1 1/2-hour test, allowing 2 or 3 data points to be taken.

(3) Slurry was pumped to the injector nozzle at a controlled rate (between 2.7 and 18 kg/hr) using a peristaltic variable-speed pump. The slurry's atomizer nozzle used steam to atomize the slurry into a stream of microscopic particles. The atomizer was placed in two different locations during the testing: at the dryer inlet and at the top of the dryer. This testing concluded that the preferred location for the atomizer is in the dryer inlet position.

(4) The dryer inlet and outlet steam temperatures and the cycle discharge temperatures were continuously monitored and recorded at 1-minute to 5-minute intervals during the test. Each test ran until steady-state dryer operation was reached, which usually took 15 to 25 minutes.

(5) The dried powder was collected in plastic airtight bags from the cyclone's collection box. These samples were immediately sealed, cataloged, and weighed. The sample collection procedure did not require the system to be shut down.

(6) The testing continued by repeating steps 3, 4, and 5 using higher slurry flow rates.

(7) The wetness of each dried powder sample was measured by removing approximately 30 grams and weighing this smaller sample before and after it was dried in a baking oven. The oven's temperature was set at 104°C.

(8) The data collected from each test were entered into a data reduction computer program to determine such important information as:

- heat balance
- actual heat transfer in the dryer
- calculation of the dryer's heat transfer coefficient
- particle loading ratio

STEAM DRYER DATA SUMMARY

A total of 39 tests were run. Twenty-four tests were performed with slurry feedstock; fifteen tests were run with just water injection (for purposes of instrument calibration and equipment debugging); twenty two tests were conducted with a clay powder feedstock; and two tests were conducted with temperature-sensitive materials - coffee creamer and a food sweetener, maltodextrin-100.

Figure 8 displays a photograph of a typical clay slurry with a wetness of 50 percent (dry basis) before its injection into the dryer and the dried powder resulting from the steam atmosphere drying. The final measured wetness is plotted in Figure 9 as a function of particle loading. This figure shows that the powder exit dryness remains low despite an increase in particle loading; an encouraging result.

ENERGY SAVINGS AND SYSTEM COST ANALYSIS

A steam dryer energy savings and system cost analysis was also conducted as part of the Phase I Feasibility Study. This analysis combined the thermodynamic analysis computer programs of the steam atmosphere dryer and the standard air dryer systems with a component materials cost and labor analysis program to determine the following comparative characteristics for both the standard air and steam atmosphere with recompression systems: system materials and engineering labor costs, operation and maintenance costs, energy cost savings per year, overall system cost savings per year, simple payback, and cost per kg of evaporated water. The validity of the thermodynamic computer programs for analyzing the standard air and steam dryer cycles was demonstrated in work conducted for Phase I.

In order to predict the steam and air dryer system's material and labor costs, a computer program was written that utilized previously published and/or new component price quotations for the standard air spray dryer and indirectly heated steam atmosphere dryer systems. The computer model's results were then compared against quotations received for complete air spray dryer systems. The comparisons between the quoted price and the computer price model predictions revealed excellent agreement.

A summary of the percentage cost comparisons by component is given in Table 1. From Table 1 it is clear that the steam components that have the most influence on the cost of the steam dryer system are the steam dryer (20 percent of total system cost), the steam compressor and electric drive (26 percent), the steam ducting and piping (1.7 percent), and miscellaneous costs (4.5 percent). The cost functions for these components are considered to be conservative; that is, they are more expensive than what may be actually realized in a fully developed system. Thus it is thought to be appropriate to use a range for the simple payback. This confidence range will identify a simple payback for the system that falls between +5 to -10 percent of the value calculated using the above component cost functions.

TABLE 1. DRYER COMPONENT COST COMPARISONS AND ECONOMIC ANALYSIS PARAMETERS

Steam Cycle Materials and Assembly Labor	Percent of Total Cost	Air Standard Cycle Materials and Assembly Labor	Percent of Total Cost
Steam Compressor	23		
Steam Blower and Motor	3.2	Air Circulator and Motor	2.9
Electric Motor and Coupling	3.0		
Gearbox	3.4		
Compressor Lube System and Base	2.3		
IRIS Steam Dryer	20	Spray Dryer and Atomizer	37.7
Steam Cyclone	8.3	Air Cyclone	19.3
Auxiliary Steam Heater	3.1	Air Heater	7.9
Feedstock Preheater	0.6		
Steam Ducting and Piping	1.7	Air Ducting	3.7
Controls and Insts.	2.8	Controls and Insts.	3.0
Misc. Costs (7.5 Percent Total)	4.5	Misc. Costs (5.0 Percent Total)	1.5
SUBTOTAL:			
Engineering Labor	11	Engineering Labor	11
15-Percent Margin	13	15-Percent Margin	13

Once the thermodynamic baseline system for the steam atmosphere dryer system was determined, a parametric analysis was conducted to determine the economic characteristics of the steam dryer system relative to the standard air dryer system. The principal economic characteristics considered were: simple payback, cost per kg of evaporated water, total cost savings per year, and estimated cost for the steam dryer system.

The simple payback was determined based on the net difference in the cost to operate both types of systems per year divided into the cost of the steam atmosphere system as shown in the following equation.

$$\text{Simple Payback (S.P.)} = \frac{\$_{\text{steam dryer}}}{\$_{\text{O\&M, air}} - \$_{\text{O\&M, steam}}}$$

where:

$\$_{\text{steam dryer}}$ = cost of the steam atmosphere dryer system

$\$_{\text{O\&M, air}}$ = yearly cost to operate the air dryer using gaseous fuel and operation and maintenance costs (see cost functions for air system)

$\$_{\text{O\&M, steam}}$ = yearly cost to operate the steam dryer using electric power and operation and maintenance costs (see cost functions for steam system)

In this analysis it was assumed that the prime mover for the steam compressor was an electric motor and that any auxiliary steam heating requirements were provided by burning natural gas. All heat input for the air atmosphere dryer was in the form of natural gas. The analysis did not consider the effect of depreciating hardware costs, tax deductions, the inflation costs for the natural gas or electric utilities, or the present value of investment monies. This simple payback analysis provides a first order analysis that is consistent with the degree of accuracy available from the cost model.

Some of the results of the simple payback analysis are given in Figure 10. Figure 10 reveals that a simple payback of 2.5 to 1.5 years is available for the steam atmosphere dryer system. This is considered very acceptable to the drying industry. The higher simple payback for a drying system of 2273 to 3182 kg/hr is due to the need for a steam compressor whose size is incrementally relatively large for the steam volume flow rate associated with 2273 to 3182 kg/hr. The cost for a steam atmosphere dryer system indicates a cost range from $1 million to $2.5 (US$) million, depending on the dryer size.

An interesting cost comparison between the steam and air dryer systems is the estimated cost to evaporate a kg of water in either the steam or air dryer system. The economic analysis has shown there is a 35-percent reduction in cost to evaporate one kg of water using the steam atmosphere dryer rather than the air dryer system (from 0.0036 US$/$kg_{evap}$ to 0.0023 US$/$kg_{evap}$).

In preparing Figure 10, assumptions were made for the operating hours per year (6525 hrs), electric power cost (5¢/kWh), and natural gas costs ($3.5/MMBtu). These costs are typical of the prevalent cost for utilities and the operating hours (i.e., two work shifts) for the U.S. drying industry. A parametric analysis using the electric and natural gas utilities and the system operating hours is interesting and useful. The results of Tecogen's parametric analysis for these variables indicate, for example, that the cost of electricity and gas can be as high as 6¢/kWhr and as low as $2.5 to $3/MMBtu, respectively, before the steam dryer system's simple payback exceeds 3 years. It is also interesting to note that a 15-percent increase in gas utility cost will result in a 25-percent increase in total cost savings when the steam dryer system is used. Similarly, it may be shown that even a 45- to 50-percent utilization factor (i.e., 4000 to 4380 hours per year) would still keep the steam atmosphere drying system from exceeding the 3-year simple payback criterion.

CONCLUSION

The economic cost savings analysis conducted during this task indicates that the steam atmosphere drying system will enable a 30-percent reduction in the cost to dry a wet feedstock and thus provide a cost savings of more than $100,000 per year. These savings can be provided with a simple payback of less than 2 years. These results are clearly very favorable to the marketing of the steam atmosphere dryer.

This study also determined that the typical "smaller" dryer of 2273 to 3410 kg/hr_{evap} capacity will cost $1 million to $1.25 million. Larger dryers (typically in the range of 6820 to 9080 kg_{evap}/hr) will cost $1.7 million to $2 million. These costs are high enough to attract current manufacturers of air dryer systems whose average unit sale is in the $1 million to $1.5 million range. Tecogen's research of present U.S. industrial drying requirements (see Task 1 summary) indicates that a 10-percent market penetration represents the sale of 336 "small" units or 93 "large" units and thus an annual steam atmosphere dryer manufacturing business of $19 million to $35 million per year for 10 years.

The energy savings incentive for the U.S. drying industry is no less compelling. Given a 53- to 57-percent decrease in drying energy requirements, the energy saved in the United States could reach 113 to 121 x 10^{12} kJ/hr if 100 percent of the dryers were displaced by steam dryers. A 1-percent displacement would still save a significant amount of energy: 1.2 x 10^{12} kJ/hr. It is also interesting to note that the atmospheric effluent of uncollected feedstock in an air dryer system would be reduced to zero, thus saving an estimated 75,000 tons/yr. Similarly, the exhaust gas emissions of NO_x and CO would be reduced as a consequence of both decreasing the energy requirements of a typical dryer system as well as changing the heating fuel source from gas to electric. For example, a 55-percent reduction in energy requirements represents a NO_x and CO savings of 2200 and 1300 tons/yr, respectively, across the United States. A change in these same pollutants as a result of changing the fuel source from natural gas to electric would be a function of the fuel of choice used in the power generating stations and the difference in the emissions cleanup and/or combustion efficiency for the dryer combustion systems. However, a low estimate of savings in NO_x and CO of 3600 and 2200 tons/yr, respectively, can be discerned from the published data of the energy heat input required for these systems. Clearly, the displacement of existing air dryer systems can contribute to energy saving as well as reduce product effluent and combustion emissions for the U.S. drying industry.

The potential U.S. energy savings of more than 1 x 10^{12} kJ/yr in addition to the reduction of stack effluent (75,000 tons/yr) and combustion exhaust products (over 2,000 tons/yr) are based on Tecogen's expectation to successfully dry temperature-sensitive as well as temperature-insensitive feedstocks. Tecogen's laboratory testing to date has clearly established the ability of the steam dryer to successfully dry clay; i.e., a non-temperature-sensitive material - a material similar to what would be dried in the chemical, stone, clay and glass, mining, and pulp and paper industrial sectors. Tecogen is continuing with attempts to dry a temperature-sensitive material and is encouraged by the success reported by other independent researchers in steam atmosphere drying of temperature-sensitive material.

ACKNOWLEDGEMENTS

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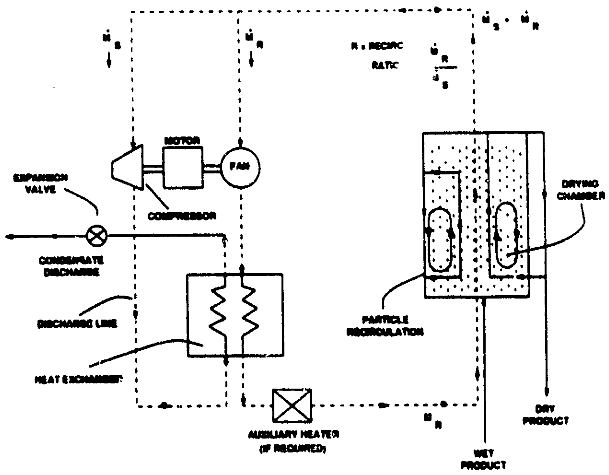

Figure 1. Concept for Direct Steam Atmosphere Dryer (DSAD) with Steam Recompression

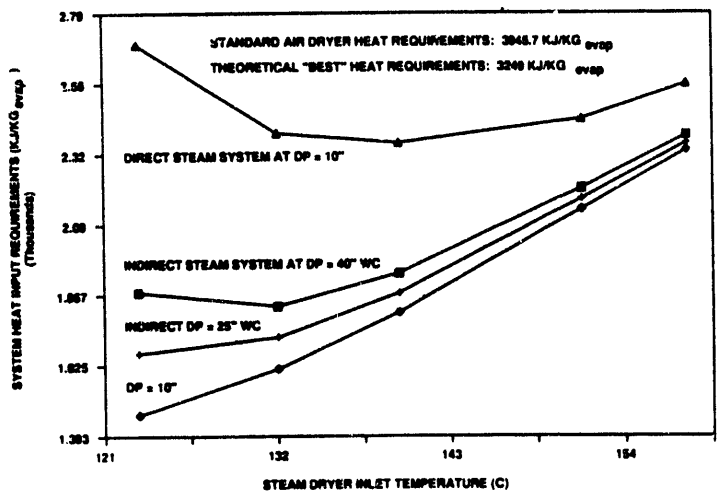

Figure 2. Steam Atmosphere Dryer Cycle System Performance for Various System Pressure Drops

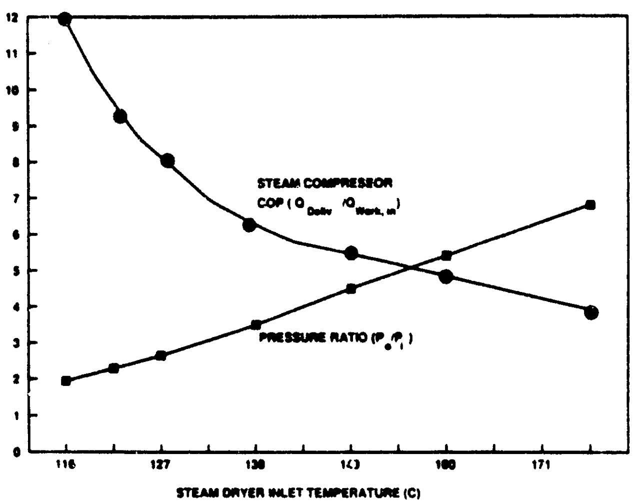

Figure 3. Direct Steam Dryer Cycle Steam Compressor Pressure Ratio (P_o/p_i)
(System Pressure Drop = 10 in. wc)

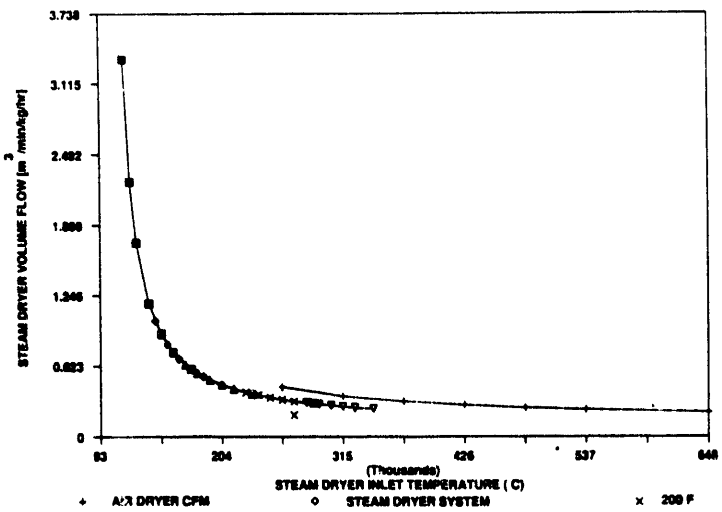

Figure 4. Comparison of Typical Volume Flow Rates for DSAD and the Air Standard Dryer System

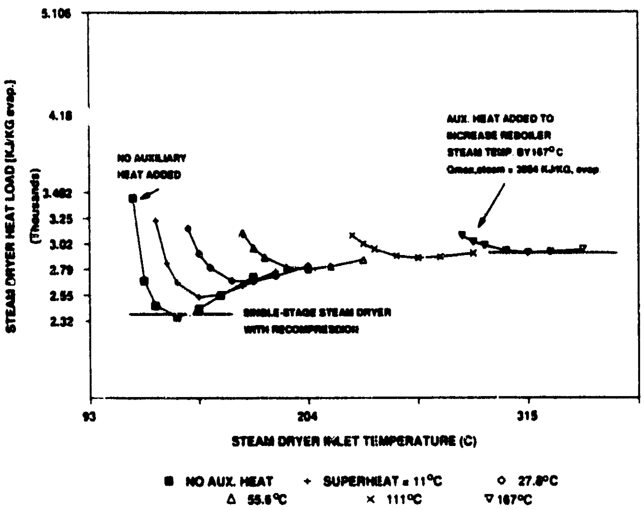

Figure 5. Effect of Aux. Heat Input on Direct Steam Atmosphere Dryer System

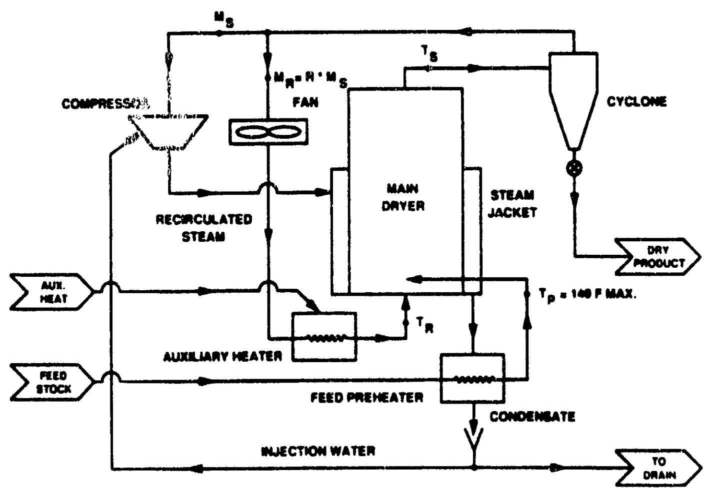

Figure 6. Indirectly Heated Steam Dryer

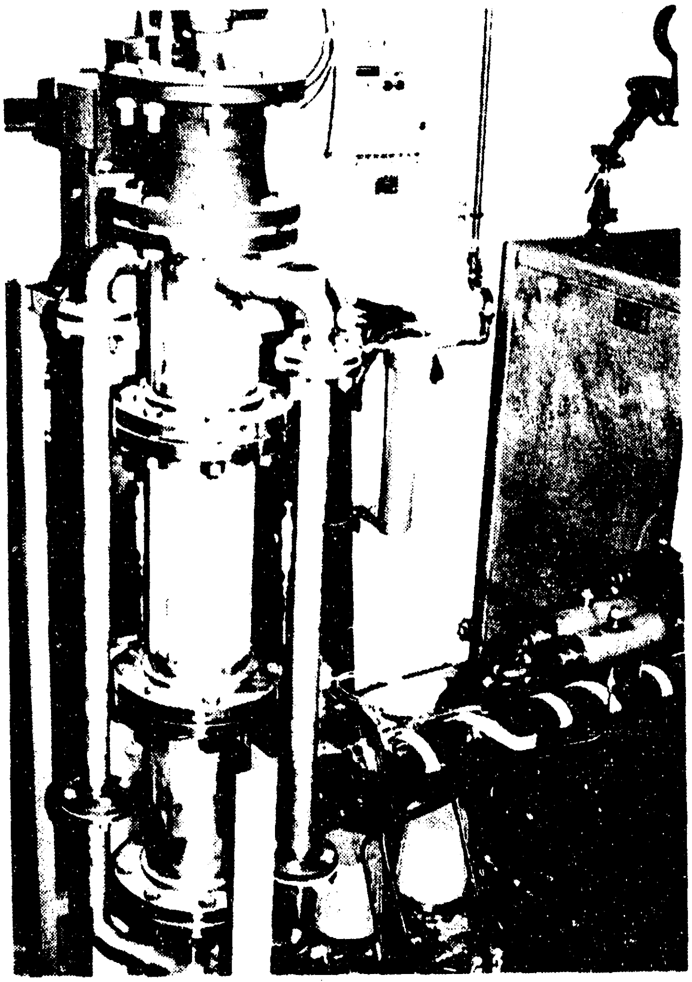

Figure 7. Tecogen's Steam Hot Test Laboratory Apparatus

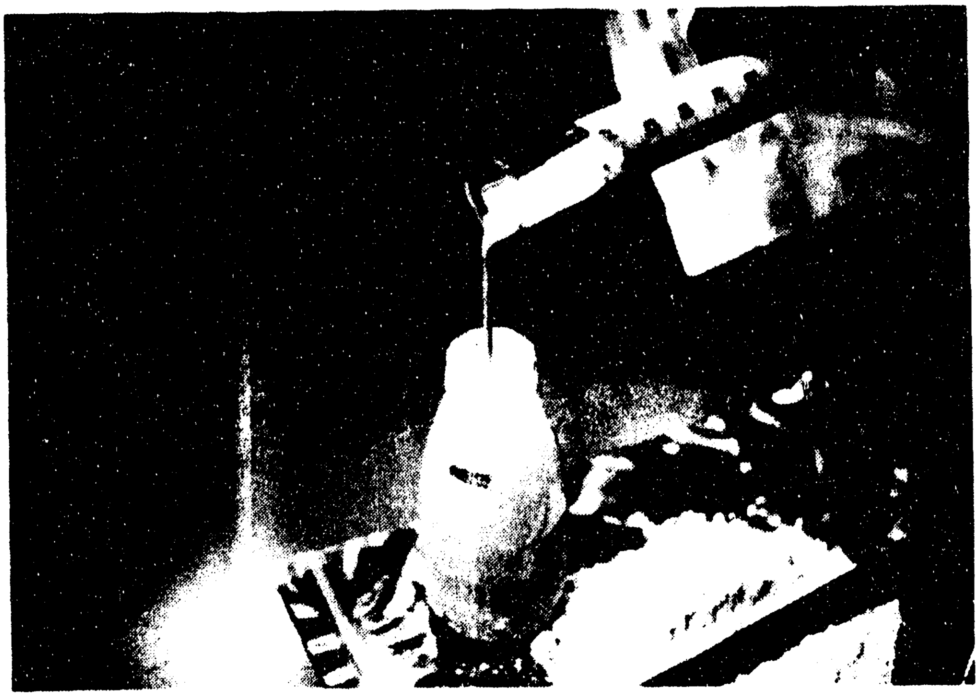

Figure 8. Clay Slurry and Steam Dried Clay Powder

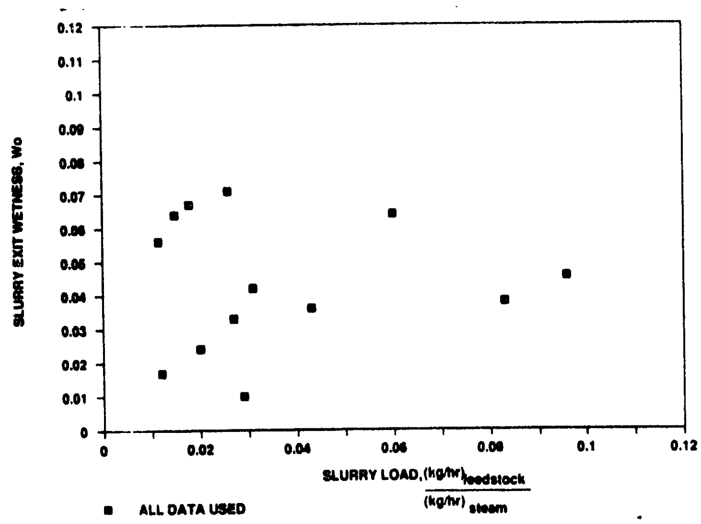

Figure 9. Steam Hot Test Data
Clay Slurry Wi = 0.5

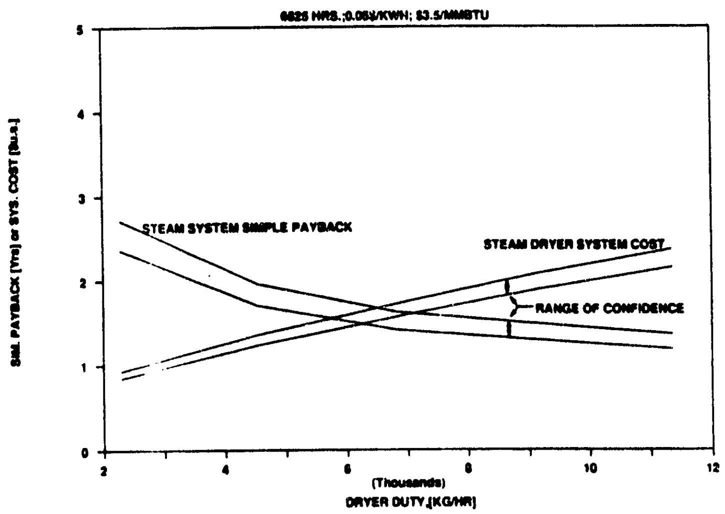

Figure 10. Simple Payback and System Cost for Steam Dryer System

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