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**Low Cost Geothermal Separators
Boundary Layer Separator Scrubber (BLISS)**

Final Report – 01/04/1999 – 02/29/2000

**D. Jung
K. Wai**

May 2000

Work Performed Under Contract No. DE-FC07-99ID13657

**For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC**

**By
Two-Phase Engineering & Research, Inc.
Santa Rosa, CA**

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Low Cost Geothermal Separators
BLISS
BOUNDARY LAYER INLINE SEPARATOR SCRUBBER

FINAL TECHNICAL REPORT

DOUGLAS JUNG AND KING WAI

TWO-PHASE ENGINEERING & RESEARCH, INC.
3209 FRANZ VALLEY ROAD, SANTA ROSA CA 95404
Office: (707) 523-4585
Fax: 528-2071
E-Mail: two-phase@juno.com

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Executive Summary

Background

Geothermal separators and scrubbers are the most expensive pieces of hardware between the wellhead and the power plant. The total installed cost per project can not only represents millions of dollars in capital expenditure, but the synergistic effects can represent a ten fold (10x) or greater financial impact on the project. Poor separating efficiencies have slugged, scaled, clogged, or eroded various components, reducing power generating efficiency; has significantly increased maintenance expenditure; and has even destroyed turbines. High-pressure drop can significantly reduce the amount of steam delivered to the power plant. For every psi reduction in pressure loss, the steam deliverability or effective reserves can be increased 0.5% to 10% and sometimes more. The pressure drop and cost savings is a function of the overall separation strategy. It is the focus of this work to not only address superior equipment performance, but to address cost-reduction goals for geothermal development, thus improving the competitiveness of this industry.

Objectives

This research and development project is a continuation of Two-Phase Engineering & Research's (TPER) search for developing low cost geothermal separators and scrubbers. With the assistance of the Geothermal Power Initiative, this project focused on an application oriented specific designs. A one-size, fits all design cannot meet the cost-reduction criteria, as such our attention was directed at resource specific problems encountered in super-heated and flash steam facilities. The original concept was to select a field and operator, and focus on a single design.

Specific project objectives were the following:

1. Select a specific geothermal field / operator with separation needs.
2. Select a specific new technology to address that need.
3. Design & build an air and water test loop.
4. Design test separator prototype and demonstrate effectiveness.
5. Analyze results and design full size separator for field test. ***

*** Not fully accomplished as of this writing. A considerable amount of effort has been dedicated to working with the field operators to quickly install a prototype for a field verification test. Loss of contact personnel, closures, sales of facilities, reorganizations have all taken a toll. These changes are beyond our control and have resulted in substantial higher cost absorbed by TPER. The field verification will hopefully begin in late 2000 at the Geysers Field.

Methods

Over the past decade, TPER has conceived a number of novel concepts to address separation problems encountered by industry. The difficulty has been finding supporters for technology development in light of the ongoing recession in the geothermal industry. With DOE support, work has primarily focused on the development of the BLISS (Boundary Layer Inline Separator Scrubber). The concept was to design several models using plexiglass and to bench test these models using an air / water system. The test would help confirm the designs and uncover any glitches. The beauty of testing with simple fluids is the ability to observe the physics, where complex two-phase modeling perhaps cannot be confirmed. The key indicators of performance were carryover, stability, capacity and pressure drop.

Results

The final prototype performances were stunning and highly successful. However, this was not the case on early standard models that showed poor to mediocre performance. Extra effort was directed at resolving complex problems and retesting, retesting and retesting. Numerous configurations were designed, built and evaluated and certain configurations demonstrated superior performance. The best models showed no non-detectable carryover, a high capacity for air and water, and moderate pressure drop. Compared to conventional New Zealand style centrifugal designs or impingement designs, the vapor capacity of the BLISS appear to be five (5) folds to ten (10) folds greater. Compared to the best-known multistage, low liquid capacity centrifugal separators, the performance of the BLISS is two (2) fold to three (3) folds greater. It is primarily the vapor handling component that makes separators large. This means BLISS requires less material for the vessel, less material to install and lower total installation cost.

Conclusions

We believe the BLISS is on the verge of a major breakthrough in separation technology. The performance is exceptional and is highly encouraging. It is probable the BLISS will overshadow our very successful LEAMS development. The LEAMS Project stands for the development of a *Low Emissions Metering Separator* for drilling, well-testing and production venting. Sandia National Laboratories recently tested this essential environmental and safety device in February, on the second largest well at the COSO Geothermal Field. The LEAMS demonstrated superior performance over conventional equipment by removing up to 99% of the escaping pollution. Although the separation principals and technology are different, we believe the BLISS (greater technical complexity) will be an even greater impact technology in the future.

On a more humbling note, the modest budget was inadequate to complete both the BLISS and BLCC (Boundary Layer Condensate Collector) testing. The BLCC was an after thought and should not have been attempted. It was an either or development but not both. Our focused attention was on the complex BLISS for a fast-track application at the Geysers. With the closure of PG&E and Unocal, Calpine has delayed the application because of the reorganizations. This is beyond our control and has been costly to TPER. We have contributed a considerable amount more funding than our required cost-share.

We are optimistic that Calpine will install a BLISS in the near future. The application is encouraging as inspection on numerous units show considerable damage to their first two turbine stages indicating poor separation performance using existing equipment. As Santa Rosa sewage water (pipeline recently approved) is pumped into the field, an even greater need will emerge. Phase 1 has been critical for developing a good understanding of the BLISS performance. We are now prepared to design a full scale BLISS for the Geysers.

The modest amount of funding provided for the Phase 1 BLISS development has served its purpose well. We know what won't work and we know what has worked well in air/water testing, and we know about earlier field prototypes and its failures. TPER believes the BLISS will result in an impact technology that will reduce the cost of developing and maintaining geothermal production at the Geysers and worldwide.

LEAMS 2000 has proven highly successful and will be a showcase DOE success story. We fully expect BLISS 2000 or worst case, BLISS 2001 to be another success story for DOE. Our objectives are to deliver cost-saving results to the industry. Thanks to DOE support, we are headed in that direction.

Recommendations

We believe a synergistic relationship between small or large innovative companies and National Laboratories could be highly beneficial. In this way, outside innovators can help bring in new ideas to cross-pollinate resulting in greater benefits to industry and NL. One of our discoveries showed that CFD modeling for complex two-phase flow is very difficult. We investigated numerous codes available on the market and found none that could fill the immediate need or budget. Hardware and mostly software cost alone would exceed \$100,000 and specific training to effectively employ such tools even more. National Labs have the capability to come up to speed more quickly and have access to some of the best software and hardware and the ability to customize. Dr. Keith Gawlik indicated a one-year time requirement to develop custom code superimposed onto Fluent. Had Dr. Gawlik been on the team, and additional funding been available, even better prediction tools and designs could be forthcoming.

Section 1: BLISS

Abstract

A new compact, low cost, and high performance separator is being developed to help reduce the installed and O&M cost of geothermal power generation. This device has been given the acronym “BLISS” that stands for “Boundary Layer Inline Separator Scrubber”. The device is the first of a series of separators, and in the case of injectates, scrubbers to address the cost-reduction needs of the industry.

The BLISS is a multi-positional centrifugal separator primarily design to be simply installed between pipe supports, in a horizontal position. This lower profile reduces the height safety concern for workers, and significantly reduces the total installation cost. The vessel can demand as little as one-quarter (25%) the amount of steel traditionally required to fabricate many large vertical separators.

The compact nature and high separating efficiency of this device are directly attributable to a high centrifugal force coupled with boundary layer control. The pseudo isokinetic flow design imparts a self-cleaning and scale resistant feature. This polishing separator is designed to remove moderate amounts of liquid and entrained solids.

Introduction

Geothermal separators and scrubbers are the most expensive pieces of hardware between the wellhead and the power plant. The total installed cost per project can not only represents millions of dollars in capital expenditure, but the synergistic effects can represent a ten fold (10x) or greater financial impact on the project. Poor separating efficiencies have slugged, scaled, clogged, or eroded various components, reducing power generating efficiency; has significantly increased maintenance expenditure; and has even destroyed turbines.

High-pressure-drop across separators reduces a depleting reservoir's ability to deliver steam to the turbine. In many instances, this choke effect in pipeline and separator strategy can reduce the amount of steam flow by up to ten percent (10%) or more in extreme cases. Better separators and scrubbers can help reduce the number of wells drilled to support the plant, enhance resource recovery, and reduce operating and maintenance cost. Today, where cost is critical, better and lower cost geothermal steam processing technology can save the industry millions of dollars and improve its competitiveness relative to other energy sources.

The geothermal industry in the majority of cases utilizes large vertical separators and scrubbers to remove liquid and dissolved and entrained solids from the vapor fraction. Alternative low-cost separators and scrubbers have been conceived to address the needs of the Geothermal Industry. The new technology development will target total *installed cost-savings in excess of 50%*; with an overall *pressure loss saving of 75%*; with an *improved steam quality and purity into the turbine in excess of 10 fold*.

BLISS Concept

The "Boundary Layer Inline Separator Scrubber" is a geothermal steam purifier that utilizes the pipeline as part of the separator. This approach enhances removal efficiency, conserves steel and reduces installation cost. A spin inducer can be installed within the pipeline to reduce the vessel size, impart a higher centrifugal force, and reduce the transitional particulate migration distance to enhance removal. The conditioned flow forms an annulus, with the liquid held by the high centrifugal force against the conduit wall, while the vapor flows through the core. This annular liquid profile enters a perforated liner where the denser material is squeezed through and removed. This liner protects the isolated liquid from re-entrainment. The shielded liquid is drained from the separator body. Fig. 1 depicts BLISS operation.

BLISS

Figure 1

The feature of this approach is especially advantageous in large-diameter conduits where increased vessel size is costly. The key focus is controlling the boundary layer at high velocities. Conventional separators encounter abrupt transitions and collisions creating considerable particulate shatter and re-entrainment. This atomizing spray nozzle effect can significantly reduce the catch efficiency as smaller particles, coupled with a reduced centrifugal force in larger pipe diameters; and longer particulate travel distance yields lower performance. Furthermore, re-entrainment from high-vapor flux is a serious problem in conventional centrifugal separators.

Re-entrainment, the mechanism of isolated solid or liquid reentering into the vapor stream is a concern addressed by the BLISS. The centrifugal force moves the liquid layer through the liner shell. The liner allows the liquid to be ejected without creating high shear and uncontrolled gas recycling. The protective liner isolates the liquid from the bulk vapor stream mitigating high transitional shearing and re-entrainment.

The pseudo isokinetic characteristic of the design helps to prevent liner and vessel scaling and plugging. Many traditional separators act as if they are a “throttling calorimeter”. High velocity, shearing, pressure drop, gradients coupled with the transition from high velocity inlet to low superficial vessel velocity evaporate or concentrate dissolved solids causing, precipitating and scale. The BLISS maintains a high velocity and pressurizes the liquid isolation chamber to prevent flashing.

This isokinetic effect does not mean no scaling will occur under normal conditions. This implies that the design will not exacerbate scaling effects through thermodynamic action. Early prototypes have shown to exhibit no scaling whereas vertical centrifugal multi-tubular designs under the same conditions have been scaled shut and rendered impotent.

The pressure drop for the BLISS is moderately low - about equivalent to the differential pressure generated across a .8 beta ratio orifice plate. A reasonable target rate is less than 2 psi. The superficial vapor operating range based on the inlet could be from 30 ft/s up to 200 ft/s. Inlet quality is highly variable but could be targeted for 50 percent or greater. A custom design could focus on minimizing pressure loss, maximizing liquid removal or maximizing exit steam quality.

Experiment

An air/water system was designed and fabricated to test the various configurations of the BLISS. Blowers, spray nozzles, re-circulating pumps, compressor, air and water flow meters, temperature and pressure indicators were installed. The basic line sizes were 3 inch, 2 inch and 1 inch. Air velocity varied 30 ft/s up to 200 ft/s. The water injection rate was varied from a fine spray up to 15 gpm. See Fig 2.

LCGSS Test Loop

Figure 2

The BLISS models were made primarily of Plexiglas so that visual observations could be made. Carryover amounts were detected by visual and diffraction techniques. At any specific blower setting, the water rate was increased with no carryover detected, a small amount of carryover, and maximum water injection for liner flooding. Internal inspection of the annulus was viewed showing the cyclonic action and perforation performance as well as carryover.

An excess of 100 rudimentary configurations have been tried, zeroing in on the more promising configurations with more detailed testing reserved for the best configurations. The testing is still incomplete; however, some of this information may be provided when the field-testing is presented in 2001.

The configuration of the BLISS has a significant effect on performance. Some designs can only remove small amounts of liquid to perhaps 2 percent without significant carry-over. Others can remove a considerable amount of bulk liquid to perhaps 85 percent but are incapable of operating without serious re-entrainment, even with small amounts of liquid. Other designs are capable of removing large amounts of liquid with virtually no carryover, are structurally unstable, and unacceptable for commercial use. Yet, some designs appear to be extremely rugged and are capable of removing greater than 85% liquid with low carry-over. These test are currently being evaluated to determine the optimum configuration.

Figure 3

Figure 3 shows a cross section of performance by four classes of BLISS designs tested on an air/water system. They show:

- A. High Liquid Capacity & Low Efficiency
- B. High Liquid Capacity & High Efficiency
- C. Low Liquid Capacity & Low Efficiency
- D. Low Liquid Capacity & High Efficiency

Pressure Drop

The pressure drop across the BLISS is moderately low for a compact design.

$$h_{wTP} = \left(\frac{W_t \left(X + 1.575(1 + X) K_g Y_g \sqrt{\frac{\gamma_g}{\gamma_L}} \right)^2}{230 K_g Y_g F_a D^2 \sqrt{\gamma_g}} \right)^2$$

$$F_a = (T - 100)(0.000014375) + 1.0009$$

$$T = F + 456$$

$$K_g = \left[0.759 + \frac{0.031}{\sqrt{D}} + \frac{0.007}{D} + \frac{0.211}{D^2} \right] + \left[1.007 + \frac{0.008}{\sqrt{D}} \right]$$

$$Y_g = 1 - \frac{0.02 h_{wTP}}{P_1 K}$$

$$K = 1.339 - (0.000068 F)$$

Where:

W_t = Mass flow rate, lb/hr

K_g = Gas flow coefficient

F = Temperature, °F

T = Temperature, R

Y_g = Gas expansion factor

F_a = Thermal expansion factor

γ_g = Gas specific weight, lb/ft³

γ_L = Liquid specific weight, lb/ ft³

D = Internal diameter, in

X = Gas quality

P_1 = Upstream pressure, psi

h_{wTP} = Pressure drop produced by two-phase, in

The above pressure drop is across the BLISS. Unlike “Vertical Designs” that often require up to six additional fittings, plus pipe, these pressure loss and cost savings are a wind fall for the BLISS system.

Field Plans

A BLISS field installation is tentatively scheduled for the Geysers at the Unit 14 Power Plant. Serious erosion damage has occurred on the first-stage and second-stage turbine nozzle and blades. It is suspected that, as a result of the steam wash process and start-up operation, high amounts of moisture and particulate may be entering the turbine causing these problems.

An 88" diameter high velocity multi-stage centrifugal separator is currently the final steam polisher prior to the turbine entry. A BLISS could be installed downstream of the vertical separator to remove carry-over and condensate prior to the turbine entry. It is tentatively projected that a 54" BLISS could be used in this steam quality enhancement program. The time frame is expected in 2001. The success of this program could result in a duplicate program at other plants at the Geysers that suffer from similar difficulties.

See Figure 4 for a possible configuration.

Figure 4

Cost Savings

The application of BLISS technology could mean replacing a high-velocity two-stage vertical cyclone 88 inches or larger in diameter by 50+ feet high, with a horizontal separator 54-inch in diameter by 20+ feet long. It is believed this technique can reduce the separator plus installation cost involving large foundations, large vertical pipe runs, unnecessary expansion loops, safety platforms, etc. by more than fifty percent (50%).

It is estimated that the installation price for an identical installed PortaTest could cost up to \$700,000. A BLISS system could be totally installed for approximately \$300,000. The pressure drop across the BLISS can be less than that of the vertical separator. The pressure loss across the extra fittings and inlet/outlet piping on a vertical separator can add an additional 50% or more unnecessary pressure loss.

At the Geysers, for every extra psi of unnecessary pressure drop, the steam output from the wells can drop by 0.7 percent. This extra production windfall is an additional cost savings and profit for the operator. Cost savings from additional steam generation, lower O&M, and lower installed cost can result in a high rate of return and improved profits.

Conclusion

BLISS is a new compact separator designed to help reduce the cost of producing geothermal energy. It is a low-profile device eliminating the need for large foundations, high safety platforms, and vertical pipe runs/expansion loops. It can be dropped in between two existing pipe supports. This lower-weight, easier to install system is expected to significantly reduce the total installed costs of new or retrofit geothermal steam separator and scrubbers.

Unlike early prototypes that were only able to remove a few percent of liquid without high carryover, these new designs are being optimized to remove moderate to large amounts of fluid. Some model configurations have been shown to handle 85% liquid, although a 30% capacity may be a more practical design. Scale resistance and structural stability are concerns addressed by the new design.

A field trial is scheduled for 2001 to test the performance of these new separators. An update on the installation and performance will be provided as information becomes available.

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Section 2: Air/Water Testing

Calibration for pump flow rate.

The experiment is to determine the capacity and flow rate of pump system. Controlling the water flow rate injection system is determined by opening position of control valve. The opening position is always adjust until percent pump rate on meter reading is reached.

Pump Flow Rate Calibration							
Container, lb	Bucket, lb	°F	Density				
4.1	48.175	80	62.2				
	0%	10%	20%	30%	40%	50%	60%
Lb /sec	0.00	0.17	0.37	0.59	0.88	1.07	1.24
Ft ³ /sec	0.00	0.00	0.01	0.01	0.01	0.02	0.02
GPM	0.00	1.23	2.69	4.23	6.32	7.73	8.91

Table 1.

The specification of pump rate is 15 gallons on maximum output. The pump rate flow curve is developed from the collected data on Table 1. The chart 1 is pump rate curve and liner equation for the pump rate curve.

The pump curve is used for determining the amount of water injection and calculating the gas quality on experiments. The quality is used to compare and determine performance of BLISS configurations.

Chart 1.

Blowers and Pump Setting for Testing

The blowers setting determined the gas flow rate and the velocity in pipeline and the pump water flow rate determined how much water injected the system. Each blower has dual speed setting either high or low. Four blowers and a pump system are built in test-loop system. The following tables list the two-phase velocity ranges that can be generated by blowers and pump setting.

BLISS Prototype Development

The collected data from each stage of BLISS protocol is used to design and improve for next stage BLISS prototype development. The objective is to test part of the BLISS prototype and evaluate how much affect this has on the overall performance of system. The prototype design for the experiment is start from smaller size in diameter of BLISS and single-stage BLISS configurations to bigger size in diameter BLISS. Figure 3 and 4 are the samples of BLISS configurations for testing. Figure 5 is a sample of BLISS prototype design for this experiment.

Figure 3.

Figure 4.

Figure 5

External Body Size Testing

The objective of the external body size testing is to define a minimum external body size in diameter without degrades the performance of BLISS system. The 4 inches and 6 inches diameter for external body are selected for experiments.

The study on following experiment the size of external body is major factor determining the capacity and performance the BLISS. The carryover is observed from outlet when system reached maximum capacity. The results show that the bigger the external body, the better performance. The bigger external body allows higher flow of air recycling without reentrainment. However, what we want is to optimize for various conditions.

Determine the Pressure Drop of Spinner.

The pressure drop of the spinner is counted as major factor for pressure loss in the BLISS system. The spinning flow generated by spinner must be eliminated in order to enable the accuracy measurements of pressure in system. The Spinning Breaker is installed in the pipeline during the experimentation. The purpose of spinning breaker is eliminated the spinning flow so that a static pressure and flow measurement can accurately taken.

Two configurations, figure 6 and 7 with equal pipe length were built for the testing. In the first configuration, only the Spinning Breaker is installed in the conduit. In second configuration, both Spinner and Spinning Breaker are installed in conduit. The pressures are measured on both end of the configuration. The following diagrams show the configurations and position of parts for the experiments

The acquired data is used for analyzing the pressure drop of the configuration. The method to determine pressure drop of spinner is different of pressure drops of the configurations. Beta ratio (β) correlation is derived from pressure drop of spinner. The pressure drop calculation is based on the method that is used in calculate the pressure drop in orifice plate. The assumption is that the pressure drop eliminates the effects of pressure recovery. Appendix I has detail calculations and conversions for beta ratio. Table 6 is summary of experiment data, pressure drops and beta ratio analysis.

Fig 6. Configuration without spinner

Fig 7. Configuration with spinner

The alignment of perforations on BLISS performance.

The objective of the testing is to determine the perforations alignments how much affect the performance of BLISS. The M100-2 figure 9 and M100-3 figure 10 are selected for the experiments and results list in table 7. The model M100-2 or M100-3 is put into 4" external body for testing.

Performance of Perforations Alignment			
Model	Maximum Water Flow Ratio		
	Blowers Setting		
	2 Low	4 Low	4 High
M100-2	2%	2%	30%
M100-3	2%	2%	2%

Table 7.

The experimental data on model M100-2 and M100-3 show that the alignment of perforation in BLISS is major factor affect the performance and outlet carryover rate. The M100-2 is higher flow capacity than M100-3.

Performance stage BLISS

The objective of the testing is to determine the flow capacity and performance of various stage on the BLISS. The samples of various stage are used.

The A stage systems are simple and can be built easily, but the performances are poor and less capacity generally. Also, the A-stage system has very poor air recycling. The single-stage system is only implemented in low flow and high quality system.

The performance on B+ stage system is higher flow capacity and less carryover during the experimental observations.

The following table summarizes the capacity range of testing configurations. The single-stage BLISS is on low capacity range and on high capacity range.

Slit Width Testing

This experiment was conducted to determine what gap width configurations do the best job of removing the most water, when different amounts of water are injected into the air flow. Also, the air blowers were run at 1,2,3,4: Hi throughout the experiment. We then varied the width of the slits in the individual slit groups, the angle the slits were cut at, and the diameter of pipe used in order to obtain maximum performance.

- ◆ Tests were conducted with 1", 2" and 3"
- ◆ The slits were at angles of 0 to 180 degrees from perpendicular to the pipe length.
- ◆ The slits had thickness were from .1 to two inches.
- ◆ The air blowers were set at 1,2,3,4: Hi.
- ◆ Carryover levels were measured in drops per second, usually by counting how many drops fall in 50 seconds, multiplying by 2, then dividing by 100.
- ◆ The graphs on the subsequent pages indicate the performance level of each configuration for different amounts of water flow.
- ◆ The performance level is determined by dividing the average amount of carryover for the group being analyzed by the amount of carryover for the specific configuration. Because the performance level is relative to the group, performance levels cannot be compared outside of the group by which the performance level was determined.

These are the results of the performance tests for the one, two and three inch pipes:

In this experiment we wanted to maximize two variables, the slit width and the slit angle. There were varying numbers of slits for different angle configurations, and the area of the pipe wall that was cut out to allow flow was different for different angle configuration. On the other hand, the test to find which slit width comparisons provided the best performance yielded fairly consistent and conclusive results.

Slit Angle Testing

Throughout the experiments conducted we tested a range of slit angles, seeking the slit angle configuration that would give the optimum performance. This section is devoted to the various observations made on how the angle at which the slits are cut affects performance.

In our testing we have used tubes with slits that are 45 degrees, going along with the flow, 45 degrees going against the flow, 22 degrees, going against the flow, and 90 degrees. .

It appears that the best slit angle is one that will let the most water out while letting the least amount of air out. This is a significant part of why the tube with the slits cut is important. This escaping air creates a higher vessel pressure, which limits the amount of water that can escape and chokes performance. We have found that the best configuration limits the amount of air that can escape while allowing a lot of water to escape. The less dense air has a more difficult time escaping through the slits. Meanwhile, the denser water at slip velocity is able to force a large fraction out through the slits.

The challenge is the direction of flow can change, depending on the pseudo flow regime of the two-phase flow. A slower flow will lose its spin more quickly and travel at a different angle than a faster flow. As a result, it is important to know the direction of flow when operating at a nominal velocity, at all points along the perforated section.

Distance between slit groups testing

This experiment was conducted to determine the optimum distance between the two slits. The pipe was 2 inches in diameter. The slit width configuration, one that has shown to deliver decent performance, was kept constant throughout the tests. Also, the diameter was kept constant. We varied the distance between the two slit, the air speed, and the amount of water being injected into the flow, then testing the carryover performance by counting drops of carryover. This was usually done by counting drops for 50 seconds, multiplying by two, and dividing by 100, to get units of drop/sec.

Counting drops is a rough but acceptable way to measure carryover. The data is a little jumpy, but there is a definite trend. In the long section, water has time to slow down, so that when it gets to slits, it falls out more easily rather than jumping the gaps and continuing through the pipe.

Another reason is that some of the water is not immediately forced to the pipe wall when it passes through the spin blade. Also, the gaps seem to give the water, which has not yet been removed, time to get organized after getting chopped up. When it gets organized into larger drops the water is easier to remove.

Pipe Thickness Testing

This experiment was conducted to get a better idea of how the thickness of the separator pipe's walls affects the performance of the separator. We tested different pipes schedules. The plastic effectively sealed the slits and did not allow the water or air to pass through them, but the slits may still have had some effect on the behavior of the pipe, because they could affect the flow on the inside of the pipe. From observation of performance, and considering the significant difference in results, it is probable that the effect these three extra slits is negligible. Each pipe was three inches in diameter. All four air blowers were set on low.

	A	B
velocity head (in. H ₂ O)	2.50	3.38
total head (in. H ₂ O)	11.63	13.63
vessel pressure (in. H ₂ O)	2.90	2.60

Carryover tests:

	A	B
zero carryover level (% max flow)*	18%	15%
80% of max. flow (max. flow with recirculation valve open)*	2.1 drops/sec. carryover	5 drops/sec. carryover
max. flow with recirculation valve closed (approx. 15 gpm.)	lots of spray (approx. 100 drops/sec.)	9 drops/sec. carryover

Apparently the A tube does a slightly better job of taking out small amounts of water, but the B tube does a far better job of removing large amounts of water. At about 8 gallons per minute, the A tube had about half as much carryover, but both tubes had small amounts of carryover. At about 15 gallons per minute, the B tube still had a relatively small amount of carryover but the thinner tube had about ten times as much as the B tube. Also, it should be noted that the A tube tends to expel the water fairly rapidly, taking air out of the tube along with it, while the B tube tends to expel the water at a slower speed and not nearly as much air seems to be escaping along with the water. This is likely to be important in understanding the differences in performance of these two tubes.

Centrifugal force of air

This experiment was conducted to determine the centrifugal force of the air spinning inside the pipe. In order to do this we used 2" pipe with one slit group. We varied the air speed and slit group. We measured the centrifugal force by measuring the pressure in the vessel, into which the air escapes and equalizes. The higher the centrifugal force, the higher the equalized pressure inside the vessel.

The results of this experiment were surprisingly good. The data came out to be within tolerances and linear. For a given setup, the centrifugal force exerted by the air from the spin blade, could be easily calculated with satisfactory accuracy.

Centrifugal force of water

This experiment was conducted to determine how the centrifugal force of the water affects the amount of carryover. The slit configuration and diameter was kept constant. The pipe was 2 inches in diameter. The air speed was varied as were the amount of water injected, as were the slit group, and the spin blade. Carry-over was then measured.

Gas Recycling Testing

In past experiments we noticed that tubes that tend to let out more air with the escaping water tend to perform more poorly. This is because the enclosure, which contains the separator tube does not allow air to escape. When the air is re-entering the tube it tends to prevent water from escaping, choking performance. In this experiment we aimed to find which tubes do the best job of letting out the least amount of air while still letting out sufficient amounts of water.

There are two methods in which we monitor how easily the air was escaping from the tube. First is to measure the pressure inside the vessel. The advantage of this method is that it is easy and precise. The disadvantage is that it is only useful for these comparisons and does not actually measure how much air is escaping and re-entering the tube. The other method is to compare air velocity measurements to determine how much air is exiting the tube. We did this by measuring the velocity head before and after the separator tube, with the vessel open, and then again with the vessel closed, and then calculate what percentage of the air is escaping out of the gaps when the case is open. The equation is used to calculate the percentage of air escaping when the case is open:

$$A = 100 \left(1 - \frac{V_{uc} V_{do}}{V_{uo} V_{dc}} \right)$$

A is the percent of air escaping through the slits when the case is open

subscript u denotes upstream measurement

subscript d denotes downstream measurement

subscript o denotes open vessel

subscript c denotes closed vessel

This method tells us how much air is escaping when the case is open, not how much is escaping when the case is closed. We believe the two quantities are approximately proportional.

The first test we performed was with a tube T. We started by covering up all the gaps except the first, and measuring the vessel pressure and upstream and downstream velocities with the case open and closed. We then uncovered the gaps, and repeating the measurement process each time.

The second test we performed was to take the measurements described above on three different styles of tubes to determine how much air escapes each style of tube. We tested three different styles of tubes, we found that the tube with the gaps angled at A direction of flow in the pipe performed significantly better than the other two tubes. It should be kept in mind that this tube had somewhat less flow area than tube B and less flow area than tube C. This can help perform a bit better, but only partially accounts for the increased performance of the tube. It is apparent that a tube with A gaps to the flow within the pipe do the best job of allowing the least amount of air to escape, while still allowing an acceptable amount of water to escape.

Appendix I

General Equations

The derivation of spinner beta ratio (β) correlation is based on the Murdock equation. Two equations have been developed for calculating the differential pressure of gas and two-phase flow.

Equations Part I: gas-phase flow rate

$$W_g = 359 S F_a F_m F_e D^2 Y \sqrt{h_w \gamma_g} \quad (1)$$

$$S = 0.598 \beta^2 + 0.01 \beta^3 + 0.00001947 \beta^2 (10 \beta)^{4.425} \quad (2)$$

$$F_a = (T - 100)(0.000014375) + 1.0009 \quad (3)$$

$$F_m = 1 \quad (4)$$

$$Y = 1 - \frac{(0.41 + 0.35 \beta^4) h_w}{27.7 P_1 K} \quad (5)$$

$$K = 1.339 - (0.000068 F) = C_p / C_r \quad (6)$$

$$T = F + 456 \quad (7)$$

The above equations are used to derive spinner beta ratio.

Equations Part II: two-phase flow rate

$$W_t = \frac{359 K_g Y_g F_a (D \beta)^2 \sqrt{h_{wTP} \gamma_g}}{X + \frac{1.26(1 + X) K_g Y_g}{K_L} \sqrt{\frac{\gamma_g}{\gamma_L}}} \quad (8)$$

$$K_L = 0.598 + 0.01 \beta + 0.00001947 (10 \beta)^{4.425} \quad (9)$$

$$\begin{aligned}
K_g = & [0.5993 + \frac{0.007}{D} + (0.364 + \frac{0.076}{\sqrt{D}})\beta^4 + \\
& 0.4(1.6 - \frac{1}{D})^5(0.07 + \frac{0.5}{D} - \beta)^{\frac{5}{2}} \\
& - (0.009 + \frac{0.034}{D})(0.5 - \beta)^{\frac{3}{2}} + (\frac{65}{D^2} + 3)(\beta - 0.7)^{\frac{5}{2}}] \div \\
& [1 + 0.000015(830 - 5000\beta \\
& + 9000\beta^2 - 4200\beta^3 + \frac{530}{\sqrt{D}})]
\end{aligned} \tag{10}$$

$$Y_g = 1 - \frac{(0.41 + 0.35\beta^4)h_{wTP}}{27.7P_1K} \tag{11}$$

Two-Phase Pressure Drop

Part III: Two-Phase Pressure Drop for spinner with beta ratio: 0.801

$$h_{wTP} = \left(\frac{Wt \left(X + 1.575(1 + X)K_g Y_g \sqrt{\frac{\gamma_g}{\gamma_L}} \right)}{230K_g Y_g F_a D^2 \sqrt{\gamma_g}} \right)^2 \tag{12}$$

$$K_g = [0.759 + \frac{0.031}{\sqrt{D}} + \frac{0.007}{D} + \frac{0.211}{D^2}] \div [1.007 + \frac{0.008}{\sqrt{D}}] \tag{13}$$

$$Y_g = 1 - \frac{0.02h_{wTP}}{P_1K} \tag{14}$$

Example 1

Following is an example calculation of beta ratio by using experiment data from Table 6.

Given data from experiment

$$P_1 = 14.7 \text{ psia}$$

$$F = 95 \text{ F}$$

$$D = 3.068 \text{ in}$$

$$W_g = 1090 \text{ PPH}$$

$$h_w = 5 \frac{11}{16} \text{ in}$$

Properties of gas can be found from gas table

$$\gamma_g = 0.072 \text{ lb/ft}^3$$

$$\mu_g = 0.0188 \text{ cp}$$

Since the experiment was conducted in single-phase system, Equations in part I are selected for calculating the beta ratio of spinner.

Iteration is required to solve the problem.

Trial 1: assumed $\beta = 0.75$ that give $W_g = 898 \text{ PPH}$

Trial 2: assumed $\beta = 0.85$ that give $W_g = 1408 \text{ PPH}$

Trial 3: assumed $\beta = 0.78$ that give $W_g = 1014 \text{ PPH}$

Trial 4: assumed $\beta = 0.82$ that give $W_g = 1214 \text{ PPH}$

Trial 5: assumed $\beta = 0.79$ that give $W_g = 1059 \text{ PPH}$

Trial 6: assumed $\beta = 0.801$ that give $W_g \approx 1090 \text{ PPH}$

The solution is found on trial 6.

Nomenclature

W_t	= Mass flow rate, lb/hr
W_g	= Mass flow of gas, lb/hr
K_g	= Gas flow coefficient
K_l	= Liquid flow coefficient
K	= C_p/C_r , ratio of specific heats
F	= Temperature, °F
T	= Temperature, R
Y	= Expansion factor
Y_g	= Gas expansion factor
F_a	= Thermal expansion factor
F_e	= Viscosity correction = 1.003
F_m	= Manometer factor for Hg=0.962; BF=0.992; PSI=1
γ_g	= Gas specific weight, lb/ft ³
γ_L	= Liquid specific weight, lb/ ft ³
β	= Beta ratio
D	= Internal diameter, in
X	= Gas quality
P_1	= Upstream pressure, psi
h_{wTP}	= Differential pressure head produced by two-phase, in
h_w	= Differential pressure head produced by gas-phase, in
h_f	= Frictional pressure head, in
h_s	= Static pressure head, in
h_t	= Total pressure head, in
h_v	= Velocity head, in

Pictures

Open End Test

Engineering Summer Hire
CalPoly SLO / UCD / UCSD

High Carryover

Liquid Removal Check

Clean Air – No Mist

Test Run 69

DOE / INEL Site Visit

One of Many BLISS Test Runs

DOE/ID/13657

**LOW COST GEOTHERMAL SEPARATORS
BOUNDARY LAYER INLINE SEPARATOR SCRUBBER (BLISS)**

**FINAL REPORT
01/04/1999 – 02/29/2000**

**D. Jung
K. Wai**

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