Capsule Pipeline Research at University of Missouri-Columbia Under an NSF State/IUCRC

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Abstract*—The Capsule Pipeline Research Center (CPRC) at the University of Missouri-Columbia is a State/Industry University Cooperative Research Center (S/IUCRC) funded by the National Science Foundation (NSF). The purpose of CPRC is to conduct extensive research and development in the capsule pipeline technology for transportation of coal, solid waste, grain, mail and many other types of freight. The Center's R&D is multidisciplinary including fluid mechanics, heat and mass transfer, drag reduction, compaction of coal and solid wastes, automatic control of pipelines, machine design, electromagnetic propulsion, economic analysis, and legal research. Progress in R&D since 1991 has resulted in rapid advancement in the coal log pipeline technology for transporting coal, and in great expansion in knowledge in capsule fluid mechanics, compaction science, compaction machine design, automatic control of capsule pipelines, economic model of capsule pipeline, and so on. Over 100 students participated in the Center's research; most of them have completed their degrees (B.S., M.S., Ph.D. and J.D.). Plan for the coming year (September 1, 1998-August 31, 1999) is to conduct a pilot plant test of an entire coal log pipeline (CLP) system in order to ready the CLP technology for commercial use. The Center is also expanding its research areas to solid waste compaction, grain pipeline and pneumatic capsule pipeline.*

Introduction

Capsule Pipeline is the transport of freight (solids) in capsules (containers or vehicles) moving through pipelines. When the fluid used for propelling the capsules in the pipe is air or another gas, it is called pneumatic capsule pipeline (PCP); when the fluid for propelling the capsules is water or another liquid, it is called hydraulic capsule pipeline (HCP). Both PCP and HCP have distinct characteristics and have niches or "windows of opportunity"

The University of Missouri-Columbia (UMC) has been engaged in capsule pipeline research since 1975. In 1991, UMC applied for and won the approval of the National Science Foundation (NSF) to set up a Capsule Pipeline Research Center (CPRC) as an NSF State/Industry University Cooperative Research Center (State/IUCRC). It was one of the first four State/IUCRCs established by NSF and the first pipeline research center at universities in the United States. The purpose of CPRC is to conduct extensive research and development (R&D) in capsule pipeline so that this emerging technology can be used commercially for transporting freight including coal, other minerals, solid wastes, mail, parcels and many other products.

The initial focus of the Center is in developing a special type of HCP called "coal log pipeline (CLP)" for transporting coal. This focus was selected due to a strong need for improving coal transportation nationwide, due to the promising nature of the CLP technology, and due to the initial industrial interest generated. Most of the initial sponsors of CPRC are electric utilities, coal companies, pipeline companies, and other companies that have strong interest in the development of the CLP technology. This resulted in the formation of a CLP Consortium to provide the required industrial matching funds to this NSF Center.

Also, CLP appears most promising because coal can be directly compacted into water-resistant and wear-resistant solid cylinders (capsules). This alleviates the need for encapsulating the cargo—coal, and for transporting the emptied capsules back to the pipeline intake by a separate pipeline. It enables the use of a single pipeline, instead of a dual pipeline, for coal transportation.

Another motivation was the fact that the 1990 amendment of the Clean Air Act prompted many electric utilities to shift to low-sulfur coals mined in distant places. For example, many Missouri utilities shifted to coals mined in Wyoming and Colorado, more than 700 miles away. Rail transportation costs for such coals constitute more than two-thirds of the delivered cost. Utilities were (and still are) eager to see the development of a new coal transportation technology that can break the monopoly of rail and to provide low transportation cost. About 70% of the electricity in Missouri and 60% in the nation is generated from coal. The United States uses one billion tons of coal each year, most of it is transported by rail at present.

A third reason for focusing on CLP is that, once the CLP technology is developed and commercialized, it

can be easily adapted for transporting other cargoes such as solid wastes and grain.

Progress in R&D

The strong focus on CLP and the practical approaches taken by CPRC in its research and development (R&D) have resulted in rapid advancement in the CLP technology since 1991. As early as 1994, sufficient knowledge had been gained in making water-resistant and wear-resistant coal logs that a limited field test could be conducted. Various coal logs were tested in an existing 6-inch diameter, 5-mile long pipeline in Conway, Kansas. The best logs lost less than 1% of weight during their journey through the pipe. The worst ones (two logs) broke in the pipe, but did not clog it, and were pushed out by the good logs following them. The overall test was considered a success.

Since the 1994 field test, research in CLP has been focused on rapid compaction of coal logs, and the design of a coal log machine that can economically mass produce high-quality coal logs. The machine design went through several stages. It was finally possible to design a machine that can mass produce commercial size coal logs at low cost. A test machine has been constructed and installed at CPRC in December 1997. The machine was tested successfully in 1998. It can mass produce high-quality coal logs and logs made of many other materials such as biomass wastes—woodchips, sawdust, waste paper, etc.

Remaining R&D

The remaining tasks in developing CLP technology include testing and improving the new coal log manufacturing machine; testing the coal logs produced in a 3,000-ft-pipeline pilot plant test loop, testing automatic injection, control and pumping of coal logs through the pilot plant pipeline loop, and improving a cost model of CLP that can be used for predicting the cost of commercial CLP systems. Barring unforeseen circumstances, by August 31, 1999, which is the end of the second four-year term of CPRC, the CLP technology will be ready for commercial use on a trial basis initially, and then for general use if the trial use (commercial demonstration) is successful. Three projects are being considered for possible demonstration in year 2001. There is a good chance that by the year 2001 (i.e., in about three years from now), the first commercial CLP will be in place and operating

Mission Broadening

Beginning in 1997, CPRC began to broaden its mission to cover other types of capsule pipelines in order to fulfill, or at least partially fulfill, an initial promise to NSF and the State. The first two types investigated are pneumatic capsule pipeline (PCP) for transporting mail and other products, and hydraulic capsule pipeline (HCP) for transporting compacted solid wastes, biomass and other freight. The PCP research is supported by the Sumitomo Metal Industries in Japan and by the Mid-America Transportation Center (MATC)—a center supported by the U.S. Department of Transportation. The solid waste and biomass study is being considered for support by the U.S. Department of Energy and some small power plants in Missouri interested in burning fuels made of biomass waste materials such as sawdust or waste paper.

Scope and Nature of Research

The disciplines involved in CPRC research are many. They include fluid mechanics, automatic control, compaction science, machine design, design of an electromagnetic pump based on linear induction motor (LIM), economic modeling and legal research. Researchers (participating faculty and students) span several disciplines including civil, environmental, chemical, electrical, mechanical, industrial and mining engineering, marketing and law. It is one of the largest cross-disciplinary efforts in research at the University of Missouri, and one that enjoys strongest industrial support.

CPRC's research is all-encompassing including theoretical analyses, laboratory tests, field tests, pilot plant tests, mathematical modeling, computational mechanics, economic modeling, operations research, market analysis, law research, etc. Most of the research projects under CPRC not only have advanced the technology of capsule pipelines, but also have generated a large body of new knowledge. The combination of theory, experiments and computer modeling resulted in drastic improvement of the state-of-the-art.

Major Accomplishments

Major accomplishments in the last seven years include the following:

Fluid Mechanics

The Center developed a four-regime theory to predict the behavior of capsule or coal-log flow in pipes, including its pressure gradient, capsule velocity, capsule drag and lift. The new theory can predict the capsule flow behavior under a wide range of conditions not possible with previous theories. The Center also developed a means for predicting the unsteady flow and pressure surges (water hammer) in hydraulic capsule pipelines (HCP) generated by rapid valve closing and opening associated with the multi-lock injection

and pump-bypass systems of HCP. The approach used is the method of characteristics applied to the two-phase flow of capsule-liquid.

Researchers at the Center discovered that the use of a small amount (25 ppm) of polyethelene oxide enables drag reduction of as much as 75% in capsule flow when capsules are at or above the lift-off velocity.

The Center developed a large body of knowledge in coal log abrasion (wear) in pipe, and the strategies needed for minimizing coal log wear. The strategies include maintaining the coal log flow at a velocity between 80% and 90% of the lift-off velocity, using logs of aspect ratios between 1.6 and 2.0, using logs of large diameter ratio (0.9-0.95), and using logs with round edges.

Aerodynamic equations have also been derived to predict capsule drag coefficient, capsule speed and capsule acceleration/deceleration in pneumatic capsule pipeline (PCP).

Heat and Mass Transfer

Center researchers completed a theoretical model for predicting heat transfer and drying of coal logs, and assessed practical means to heat coal in order to facilitate compaction.

Automatic Control

Center researchers designed, built, tested and demonstrated a complete system for automatic injection, ejection and pumping of capsules or coal logs through pipelines. Researchers derived the equations needed for predicting the behavior of capsule injection and pumping systems. They also invented and tested a system that can control the spacing between capsule trains in pipe (patent pending) and derived the equations for analyzing this system.

Compaction Science

Center researchers succeeded in making strong (water-resistant and wear-resistant) coal logs for pipeline transportation and developed the know-how for making strong coal logs. They tested the effects of more than 20 factors that influence the quality of coal-log compaction and found many ways to improve the coal log quality, such as: (a) having optimal moisture in the feed material, (b) compacting at optimal pressure, (c) reducing the zeta potential of coal, (d) using tapered or round exit molds,(e) achieving optimum particle size distribution, (f) heating of coal to optimal temperature, (g) using compaction pistons of a special shape, (h) using certain solid lubricants such as calcium stearate, (i) using back pressure during ejection from mold, (j) using vacuum during compaction, and (k) using Orimulsion as binder.

The Center succeeded in compacting biomass waste materials such as sawdust, wood chips, soy bean hulls, etc., and other wastes such as coal fines. Such compaction uses no binder and requires no heating of the waste materials.

The Center developed theoretical models for coal log compaction which not only improved the current theories on compaction of solids but also made it possible to predict the characteristics of large coal logs compacted based on physical parameters measured from small-scale test. It also provided a means of computer simulation of coal log compaction based on finite element method.

Machine Design

The Center designed a special machine (hydraulic press) suitable for mass production of coal logs in commercial operations (patent pending). The same machine can be used to compact other solids such as sawdust, wood chips, rice hulls, soy bean hulls, coal fines and coal-biomass mixtures. The machine is based on a three-second compaction time. It can develop back pressure during coal log ejection from the mold, enhancing coal log quality.

Center researchers built a large machine for mass production of coal logs of 5.3 inch (135 mm) diameter. They also designed a second generation compaction machine based on the rotary press (tableting machine) concept. The machine is mechanical (does not use hydraulic press) and hence is simpler and less costly than the first-generation machine.

Water Quality and Treatment

Under sponsorship by EPRI (Electric Power Research Institute) and Patricia Roberts Harris Fellowships, Center researchers studied the water quality and the treatment of the effluent of coal log pipelines (CLP). It was found that the CLP effluent can be treated in a manner similar to the treatment of the effluent of coal slurry pipelines except that the treatment cost is much less for CLP than for coal slurry pipeline due to much lower concentration of solids and much smaller quantity of water needed for CLP. The treatment cost was found to be generally less than 50 cents for each ton of coal transported by CLP.

Field Test

The Center successfully field tested the CLP technology in a 5-mile commercial underground pipeline.

Economic Analysis

Center researchers developed a sophisticated economic model for analyzing the cost of CLP and for comparing the cost of CLP with other means of transporting coal, including slurry pipeline, rail and truck. This model showed a "window of opportunity" for CLP.

Pilot Plant Design

Researchers at the Center completed the design of a pilot plant CLP consisting of a 3,000-ft recirculating pipeline having the same types of injection, ejection, pumping and effluent water treatment systems as those to be used in future commercial CLP.

Technology Transfer

Center researchers wrote a 3-volume manual of practice on the CLP technology including a legal manual. Center personnel conducted a short course on solids transport and a workshop on CLP. The Center transferred the economic model to industry. Industry has used it to analyze the economic feasibility of CLP for several commercial projects. The Center also performed market analysis of CLP, identifying places and conditions most favorable for CLP. This analysis investigated more than 20 potential commercial CLP projects and found several promising projects.

Spinoffs

Center researchers invented a new way to dissolve a drag-reducing polymer (polyethylene oxide) in water by using vacuum. The invention is expected to be applicable to many other types of powders and hence has far-reaching industrial implications.

The Center demonstrated compaction of solid wastes by using the machine developed for coal log compaction. The compacted solid wastes are densified and agglomerated, making them easier to handle and transport. Compacted hazardous waste materials can be deposited in landfills without polluting the ground water since the compacted materials are impermeable. The Center also invented a new type of "pig" made of a special resin for pipeline monitoring and capsule detection, and a new way to sense (detect) coal logs and other capsules in HCP by using a special electrode.

Education

CPRC offers a few pipeline related courses such as CE/MAE 345 Pipeline Engineering, CE/MAE 401 Advanced Topics (Pipeline Transport of Solids), CE441 Advanced Hydraulic Engineering (Pipeline Transients), and MAE 439 Two-Phase Flow. The Pipeline Engineering course (CE/MAE 345) is an ITV course (using ISDN) linked to the University of Missouri's Kansas City program. It is an elective for seniors and graduate students in civil, mechanical and other engineering disciplines.

CPRC supported and trained over one hundred students during its seven years of operation. Students with CPRC support have received 11 Ph.D., 34 M.S., 28 B.S. and 6 J.D. Seven Post Doctoral Fellows and two exceptionally qualified high school students were also supported by CPRC. The high school research participation was during summer. Two female students completed their M.S. degree studying coal log pipeline while being on Patricia Roberts Harris Fellowships.

Publications include 45 M.S. or Ph.D. theses or dissertations, and well over one hundred papers and reports. Five inventions were made: one resulted in a patent, one in conditional patent approval, two patents pending, and one patent to be filed.

Outreach

CPRC conducted two national surveys, one on pipeline education and the other on pipeline industry problems. The survey on education showed that at present only a small number of academic institutions in the United States offer pipeline related courses. The University of Missouri-Columbia is the only school that offers a course in "pipeline engineering." There is a strong need to have this and other pipeline related courses taught at universities.

The survey on pipeline industry problems found that pipeline companies spend little money in research. Their greatest concern at present is increased government regulations.

The Center's director, Henry Liu, also organized and offered in 1995 a national Workshop on Pipeline Research Needs in Leesburg, Virginia, co-sponsored by the American Society of Civil Engineers (ASCE) and eight other organizations. It resulted in the publication of an ASCE proceedings on pipeline research needs. He also led a group of national experts in freight pipelines to publish an ASCE Task Committee report on the status and future of freight pipelines.

Economic Development

Because CLP technology has not yet been commercialized, it has yet to contribute significantly to economic development. Only a few small companies have benefited financially, such as those involved in constructing the new coal log compaction machine, and those using CPRC-

developed software and information to provide consulting services to electric utilities in assessing potential CLP projects. However, a huge contribution to economic development is expected as soon as the CLP and/or other types of capsule pipelines are used commercially.

International Collaboration

Foreign countries that have indicated a strong interest in CLP include Australia, Canada, China, Indonesia, South Africa, Poland and Venezuela. For instance, China's Coal Ministry and the Metallurgy Ministry sent three visiting scholars to CPRC to learn the CLP technology. The Taiyuan University of Technology has signed exchange agreement with the College of Engineering focused on CLP technology. Finally, Japan's Sumitomo Metal Industries is sponsoring CPRC's research in pneumatic capsule pipeline, and the Japanese government (National Institute for Resources and Environment) invited the CPRC Director to Japan to give a week of lectures on capsule pipeline technology and to discuss research of mutual interest.

Future Plan

CPRC plans to complete the development of the CLP technology for commercial use by August 31, 1999, the end of CPRC's second four-year term. Remaining work for the next year includes: testing a specially-designed coal-log compaction machine for mass production of coal logs; testing the coal logs manufactured by this machine in a 3,000-ft-long pilot plant CLP; testing the injection, ejection, pumping and control of the pilot plant; finalizing the manual of practice; finalizing the economic analysis of CLP; and making the final selection of a commercial demonstration project. Other capsule pipeline research projects to be pursued include compaction of solid wastes and biomass, and use of linear induction motor for improving pneumatic capsule pipelines.

Conclusion

After seven years of intensive R&D at the Capsule Pipeline Research Center (CPRC), the coal log pipeline technology for transporting coal is heading for commercialization, and a large body of knowledge has been generated in the fields of capsule hydrodynamics, automatic control of capsule pipeline, compaction of coal logs, design of coal log compaction machine, economic analysis of coal log pipeline, legal issues concerning pipelines carrying coal and other freight, and the market for coal log pipelines. Research has also been initiated in compacting solid wastes and biomass for pipeline transportation, and in pneumatic capsule pipeline (PCP) for transporting mail and other commodities. Spinoffs include several enhanced compaction processes, a more efficient new machine for compacting solids, a new method for dissolving powder by using vacuum, and a new transducer to detect (sense) the passage of capsules or "pigs" in pipelines. The Center has trained and supported more than one hundred graduate and undergraduate students, and even two exceptional high school students. Publications include 37 M.S. or Ph.D. theses or dissertations, and well over one hundred papers and reports. Five inventions were disclosed: one resulted in a patent, one in conditional patent approval, two patents pending, and one patent to be filed.

Acknowledgment

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