0273-2289/04/113/0027–0039/$25.00

Pipeline Transport of Biomass

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Abstract

The cost of transporting wood chips by truck and by pipeline as a water slurry was determined. In a practical application of field delivery by truck of biomass to a pipeline inlet, the pipeline will only be economical at large capacity (>0.5 million dry t/yr for a one-way pipeline, and >1.25 million dry t/yr for a two-way pipeline that returns the carrier fluid to the pipeline inlet), and at medium to long distances (>75 km [one-way] and >470 km [two-way] at a capacity of 2 million dry t/yr). Mixed hardwood and softwood chips in western Canada rise in moisture level from about 50% to 67% when transported in water; the loss in lower heating value (LHV) would preclude the use of water slurry pipelines for direct combustion applications. The same chips, when transported in a heavy gas oil, take up as much as 50% oil by weight and result in a fuel that is >30% oil on mass basis and is about two-thirds oil on a thermal basis. Uptake of water by straw during slurry transport is so extreme that it has effectively no LHV. Pipeline-delivered biomass could be used in processes that do not produce contained water as a vapor, such as supercritical water gasification.

Index Entries: Wood chips; pipeline; biomass; lower heating value; straw.

Introduction

Carbon-based power generation facilities do not typically rely on delivery of fuel by highway truck. Oil- and gas-fired plants rely on pipelines, and coal-based facilities typically either are located at the mine mouth or rely on rail or ship for fuel delivery. The reason for this is the high cost and high congestion that would be associated with delivery of large tonnages of fuel to modern, large power plants.

Numerous biomass power plants are small and utilize truck delivery of fuel. However, in a previous work *(1)*, we noted that optimum size for straw- and wood-based biomass power plants in a western Canadian set-

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ting were 450 MW or greater for straw and wood from harvesting the whole forest, and that cost of power increased sharply at sizes below about 200 MW. For forest harvest residues (limbs and tops), which are more widely dispersed, the optimum size was 137 MW.

A 450-MW biomass power plant burning 2.1 million dry t/yr of wood chips would require 17 truck deliveries per hour at 20 t/truck *(2)*. Highway transportation of fuel is a significant cost element, contributing at optimum power plant size 25, 14, and 38% of the total cost of power generation from direct combustion of straw, wood from harvesting the whole forest, and forest harvest residues, respectively *(1)*. In the present work, we evaluated pipeline delivery of biomass to a power generation plant, to avoid road congestion (and likely resistance by nearby residents), and to reduce overall fuel transportation cost.

Two carrier mediums are considered for biomass: water and oil. We review the inherent economics of truck vs pipeline transport, and then evaluate a case of field delivery of biomass by short-haul truck to a pipeline terminal. We also evaluate the impact of water and oil absorption by the biomass fuel. Finally, we discuss the prospects for pipeline transport of biomass.

In this article, all costs are reported in year 2000 US dollars; Canadian dollars are converted to US at an exchange rate of 1.52 Cdn$/US$.

Inherent Economics of Truck and Pipeline Transport

Truck delivery of material has a fixed cost associated with the time required to load and unload the truck, and a variable cost that is related to the time the truck is being driven and/or the distance driven. For most biomass delivery applications, truck speed is relatively constant over the route; thus, e.g., a truck picking up straw would average about 80 km/hr on rural and district roads, and a truck picking up wood chips in a forest would average about 50 km/h on logging roads. Only if the wood chips required a significant drive over highways would there be a second higher speed portion of the trip; this effect is ignored here. Figure 1 shows cost data per kilometer for truck transport of wood chips in a typical western Canadian setting (*[3]*; D. Evashiak, personal communication, 3/03); the intercept of the lines is the fixed cost of loading and unloading, and the slope is the incremental variable cost per kilometer. Table 1 provides the equations for transport costs, including straw *(1)*. Figure 1 is adjusted to dry tonnes of biomass to make a comparison of pipeline costs easier; pipeline costs are discussed later. Typical field moisture levels for straw and wood in western Canada are 16 and 50%, respectively. The range of costs for truck transport of wood chips comes from two different types of estimate: the lower bound is from a Forest Engineering Research Institute of Canada (FERIC) study of chip transport costs from a long-term dedicated fleet, and the upper bound is based on current short-term contract hauling rates. The FERIC data are more representative of steady biomass supply to a long-term end use such as a power plant. Note that there is no change in cost with scale for any

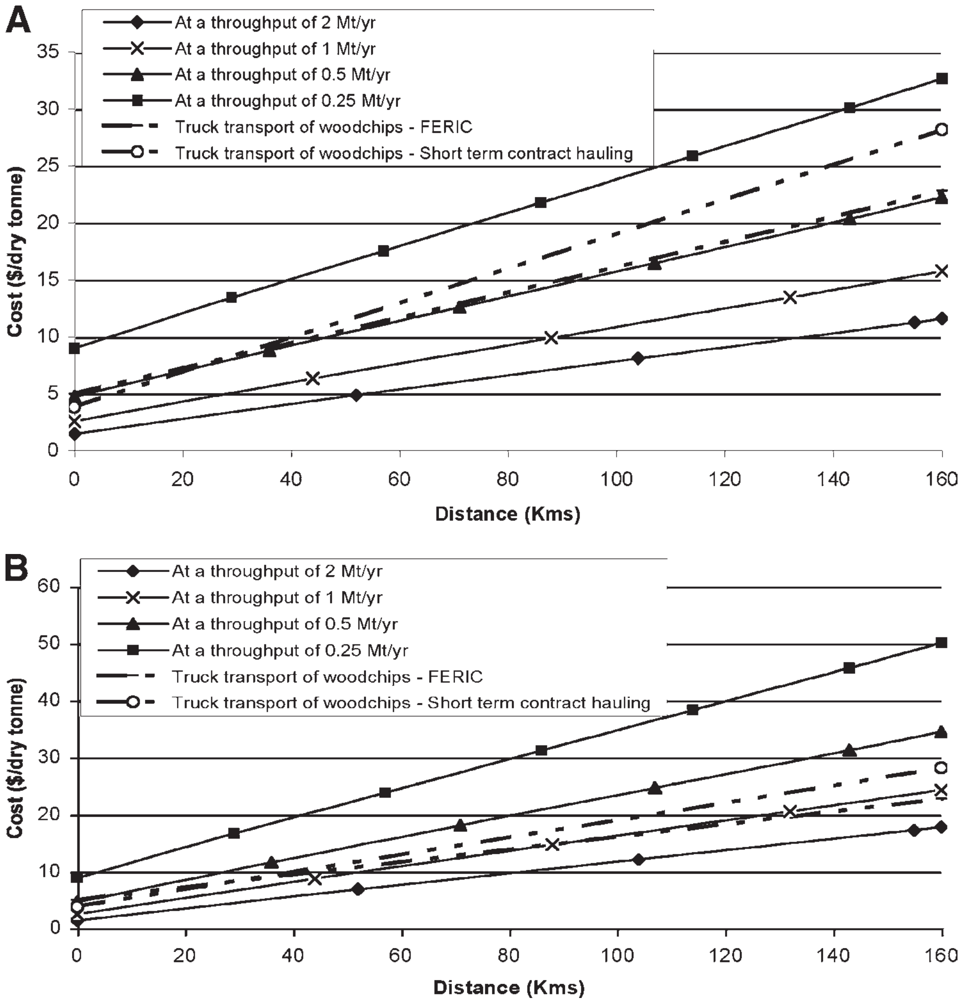

Fig. 1. **(A)** Pipeline transport cost of wood chips without carrier fluid return pipeline. **(B)** Pipeline transport cost of wood chips with carrier fluid return pipeline.

biomass application of interest; that is, the amount of biomass moved fully utilizes multiple trucks and no savings occur with larger throughput.

Pipeline transport of wood chips was studied in the 1960. Brebner *(4)*, Elliott *(5)*, and Wasp et al. *(6)* examined solids carrying capacity and pressure losses, and Wasp et al. *(6)* did a cost analysis for a 160-km pipeline with one-way transport, i.e., no water return. These studies were focused on the supply of wood chips to pulp mills, and hence water uptake by chips did not have a downstream processing impact. More recently Hunt *(7)* did an extensive analysis of friction factors in wood chip slurries in water; in the present work, we utilize his formula for the friction factor.

Table 1
Formulae for Truck and Pipeline Costs as Function of Distance

Cases	Cost ($/dry t)[a]	Distance between slurry pumping stations (km)
Two-way pipeline transport cost of water wood chip slurry		
2 million dry t/yr capacity	0.1023d + 1.47	51
1 million dry t/yr capacity	0.1355d + 2.65	44
0.5 million dry t/yr capacity	0.1858d + 4.80	36
0.25 million dry t/yr capacity	0.2571d + 9.05	29
One-way pipeline transport cost of water wood chip slurry		
2 million dry t/yr capacity	0.0630d + 1.50	51
1 million dry t/yr capacity	0.0819d + 2.63	44
0.5 million dry t/yr capacity	0.1088d + 4.80	36
0.25 million dry t/yr capacity	0.1473d + 9.07	29
Truck transport cost of wood chips (50% moisture)		
FERIC (long-term hauling)	0.1114d + 4.98	—
Short-term contract hauling	0.1542d + 3.81	—
Truck transport cost of straw (16% moisture)	0.1309d + 4.76	—

[a] d, the distance in kilometers.

More recently, Liu et al. *(8)* completed an analysis of two-phase pipelining of coal logs (compressed coal cylinders) by pipeline. In the present article, we draw on the work of Wasp et al. *(6)*, Liu et al. *(8)*, and discussions with a Canadian engineering contractor (D. Williams, personal communication, 3/03) to develop pipeline cost estimates for transporting water slurries of wood chips; these costs are also shown in Fig. 1 and Table 1.

Delivery of material by slurry pipeline has a cost structure similar to that for truck transport. The fixed cost is associated with the investment in the material receiving and slurrying equipment at the pipeline inlet, and the separation and material transport equipment at the terminus. The slope of the curve comes from the operating cost of pumping, and the recovery of the incremental capital investment in the pipeline and booster pumping stations plus associated infrastructure such as power and road access, all of which increase linearly with distance. Technically, pipeline costs would have a slight "sawtooth" shape, with a slight, discrete increase in overall cost occurring when an additional pumping station is required. Practically, most of the incremental capital cost is in the pipeline rather than pumping stations, and the sawtooth effect can be ignored. (In our analysis, the pipeline component of the total capital cost is 85% at 50 km, and 94% at 500 km.)

One key element in the pipeline scope and estimate is whether a return line for the carrying fluid is provided. This would be required in virtually

Table 2
Capital Costs for Inlet, Outlet, and Booster Station Facilities[a]

Item	Cost ($ 1000)	Remark
Inlet facilities		
Land for inlet facility	19.7	Estimated
Access roads	39.9	*(15)*
Conveyor belt	245.3	*(16)*
Mixing tank (water and chips)	61.3	*(16)*
Piping	405.1	*(8)*
Foundation for pump area	100.0	Estimated
Storage tank for water	769.3	*(16)*
Auxiliary pump (with one redundant pump)	137.1	*(8)*
Power supply line and substation	400.0	Estimated
Communication lines	40.0	Estimated
Building	236.8	Estimated
Road along pipeline	266.0	*(15)*
Fire suppression system	65.8	Estimated
Mobile stacker for dead storage	100.0	Estimated
Main pump for transport of wood chips and water mixture	2678.8	*(8)*
Pipeline for transport of wood chips to plant	58,863.9	*(8)*
Total capital cost at inlet	64,429.0	
Outlet facilities		
Building	236.8	Estimated
HVAC system to blow air	48.6	*(16)*
Conveyor belt	490.6	*(16)*
Filtration tank	3.4	*(16)*
Water intake tank	769.3	*(16)*
Water supply lines from water source	42.6	*(8)*
Auxiliary pump (with one redundant pump)	137.1	*(8)*
Main pump for water return	2262.3	*(8)*
Return water pipeline	41,897.2	Estimated
Total capital cost at outlet	45,887.9	
Booster station facilities		
Substation	400.0	Estimated
Booster pump for mixture	1283.0	*(8)*
Booster pump for water	1017.5	*(8)*
Building	19.7	Estimated
Access roads	4.0	*(15)*
Land	0.7	Estimated
Foundation for pump area	100.0	Estimated
Total capital cost at booster station	2824.9	

[a] Two-way pipeline, 819 mm of slurry, 606 mm of water, 2 million dry t/yr, 104 km.

all circumstances if the carrying fluid were a hydrocarbon (e.g., oil) and would be required for water if upstream sources were not available, as might occur in a forest cut area, or if downstream discharge of separated water were prohibited. Tables 2—4 show the scope and cost estimate included in a two-way pipeline (i.e., one with return of the carrier fluid).

Table 3
O/M Cost for Inlet, Outlet and Booster Station Facilities[a]

Item	Cost ($ 1000)	Remark
Inlet facilities		
Electricity	1775.9	
Maintenance cost	423.0	
Salary and wages	1080.0	4 per shift
Total O/M at inlet	3278.9	
Outlet facilities		
Electricity	1448.0	
Maintenance cost	331.1	
Salary and wages	540.0	2 per shift
Total O/M at outlet	2319.1	
Booster station		
Electricity	2627.7	
Maintenance cost	38.5	
Total O/M at booster station	2666.2	

[a] Two-way pipeline, 819 mm of slurry, 606 mm of water, 2 million dry t/yr, 104 km.

Table 4
General Economic and Technical Parameters

Item	Values
Life of pipeline	30 yr
Contingency cost	20% of total cost
Engineering cost	10% of total capital cost
Discount rate	10%
Operating factor	0.85
Power cost	$50/MWh
Velocity of slurry	1.5 m/s
Velocity of water in water return pipeline	2.0 m/s
Maximum pressure	4100 kPa
Pump efficiency	80%
Scale factor applied to inlet, outlet, and booster station facilities excluding pumps	0.75

Key elements at the upstream end are materials receiving from trucks, dead and live storage, slurrying, and pipeline initial pumps. Key elements along the pipeline are the slurry and return pipeline and booster pumping stations. Key elements at the discharge end are slurry separation and drainage of the wood chips, and material transport to the biomass processing facility. As already noted, pressure drops, pumping requirements, and the overall estimate are based on water as the carrier fluid.

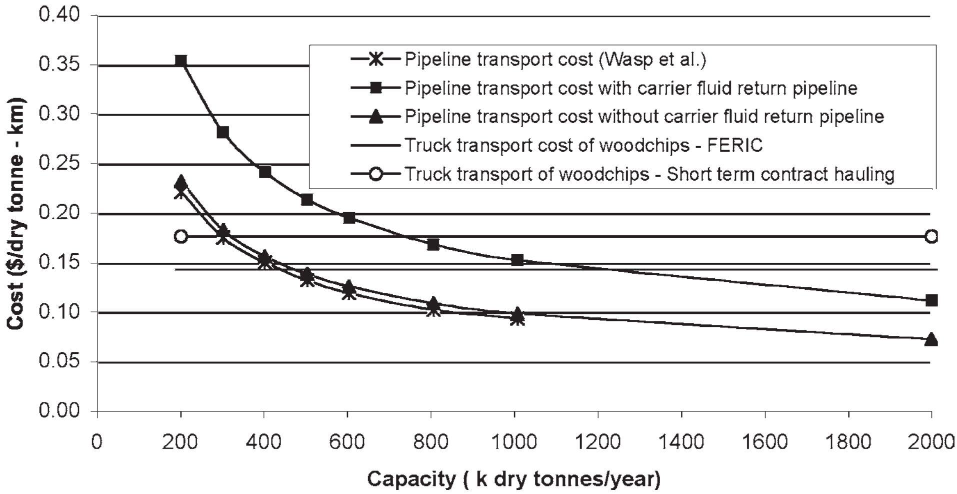

Fig. 2. Pipeline and truck transport cost of wood chips at fixed distance of 160 km.

Note that unlike truck transport, there is an economy of scale in slurry transport of materials, since larger throughputs benefit from an economy of scale in construction of the pipeline and associated equipment, and in lower friction losses in larger pipelines.

Figure 2 compares the total transport costs of wood chips by truck and by pipeline, for an arbitrary fixed distance of 160 km. The basis of the cost estimate is a wood chip concentration of 27% by volume at the inlet end and 30% by volume at the outlet end. The close agreement between the estimating formulae of Liu et al. *(8)* and the results of Wasp et al. *(6)* for a one-way pipeline is evident. The one-way pipeline cost estimates were cross-checked against a recent estimate of two short large-diameter liquid pipelines in western Canada (D. Williams, personal communication, 3/03), and showed good agreement. Figure 2 shows the impact of scale on pipeline costs, as compared with the cost of truck transport, which is independent of scale. (The formulae of Liu et al. *(8)* and the data from Bantrel [D. Williams, personal communication] suggest a capital cost scale factor for pipelines of 0.59—0.62; the data of Wasp et al. *(6)* as not specific enough to calculate a comparable figure.) Figure 2 also shows the significantly higher cost for a two-way pipeline that returns carrier liquid to the inlet end.

From Figs. 1 and 2 it is clear that the marginal cost of transporting biomass by pipeline at a concentration of 30% is higher than truck transport at capacities <0.5 million dry t/yr (one-way pipeline) and 1.25 million dry t/yr (two-way pipeline) at a distance of 160 km. The implications of this finding are discussed in the next section.

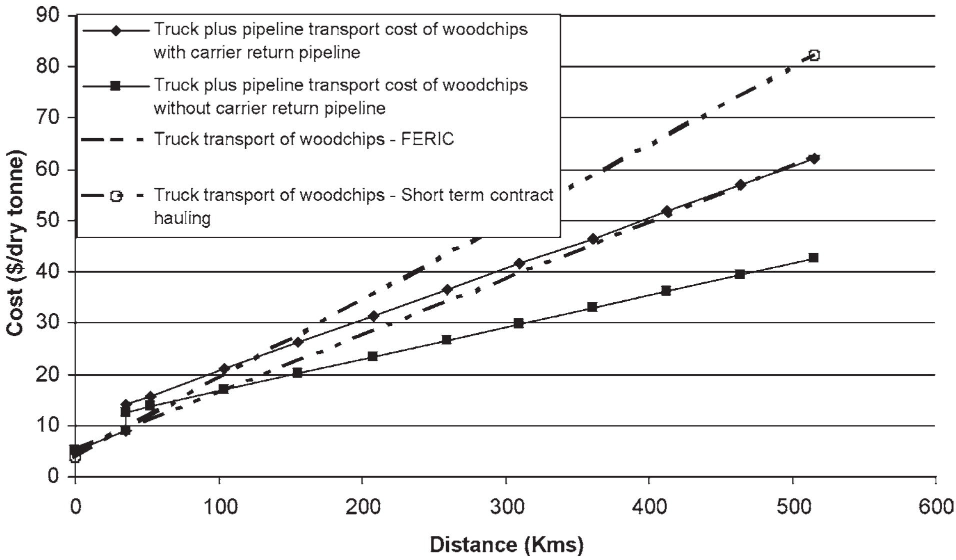

Fig. 3. Comparison of integrated truck/pipeline transport vs truck-only transport of wood chips at capacity of 2 million dry t/yr.

Practical Application: Integrated Truck/Pipeline Transport of Biomass

Any real application of pipeline transport of biomass from a field location (as opposed to mill residue) will normally require an initial truck haul to get the biomass to the pipeline inlet. This means that the fixed costs associated with both truck and pipeline transport are incurred. Thus, e.g., truck hauling of 2 million dry t/yr of biomass to a pipeline inlet at an average haul distance of 35 km *(1)*, as might occur in a whole-forest harvest operation, with further transport of biomass by one- or two-way pipeline would have cost curves as shown in Fig. 3. The alternative of transport by truck alone is shown by the dashed line in Fig. 3.

Since by inspection of Fig. 1 all pipelines with a capacity of <0.5 million dry t/yr (one-way) or 1.25 million dry t/yr (two-way) have a higher incremental cost (slope) per kilometer than the alternative of hauling by truck, it is clear that pipelines below this capacity cannot compete with the alternative of leaving the biomass on the truck for the extra distance. In the example illustrated in Fig. 3, at 2 million dry t/yr the minimum pipeline distance to recover the fixed costs of the pipeline as compared to truck haul are 75 km for a one-way pipeline (in addition to the initial 35-km truck haul to the pipeline inlet), and 470 km for a two-way pipeline (again in addition to the initial truck haul); pipeline distances shorter than this are less economic than continued hauling by truck. Hence, pipelining of truck-delivered biomass at a concentration of 30% is only feasible at both large capacity and medium to long distances.

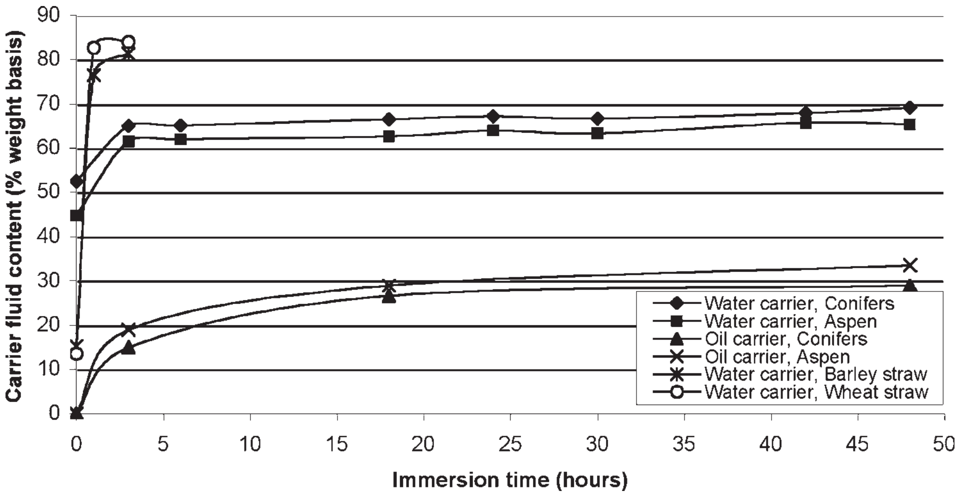

Fig. 4. Carrier fluid content of biomass after different hours of immersion in carrier fluid.

Absorption of Carrier Fluid by Biomass

We performed a series of simple experiments to explore the uptake of carrier fluid by biomass. Fresh wood chips, both hardwood (aspen) and softwood (spruce), were kept sealed and cool until immersion in room temperature water or oil; they were drained and dried to determine moisture level. Water drainage was brief, about 1 min., although one test of a longer drainage period showed a negligible impact of longer drainage times. The oil used in our study is a heavy gas oil fraction from Syncrude Canada, with a nominal boiling range of approx 325—550°C and a viscosity of 1.3 Pa s at 20°C. This type of oil is typical of an industrial-grade furnace oil. Wood chips were drained of oil for 1 hr before weighing. Figure 4 shows the carrier fluid content of biomass after exposure to carrier fluid for varying periods of time. Note that immersion time can be related to pipeline distance because at a typical slurry velocity of 1.5 m/s, the slurry would travel 5.4 km/h.

The choice of an oil carrier requires a tradeoff between the viscosity of the carrier, which drops with lower boiling range of the oil fraction, and the value of the carrier, which increases with lower boiling range. At one extreme, a diesel fraction would have low viscosity but has such a high value as a transportation fuel that its use as a thermal fuel would be cost prohibitive. At the other extreme, a residuum fraction would have low value but such a high viscosity that transport of the slurry would likely be prohibitive in operating (pumping) cost. In the present study, we have arbitrarily selected a heavy gas oil as the balance between these competing considerations.

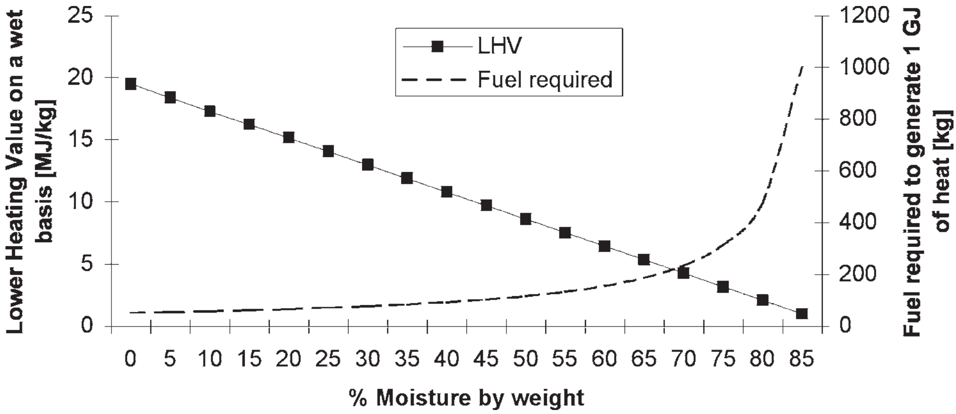

Fig. 5. Moisture content vs LHV and fuel requirement of wood chips.

During water immersion, 1 kg of mixed spruce and aspen wood chips at an average 50% water content would pick up an additional 0.51 kg of water and reach a terminal moisture level of about 67%. Water uptake is quick; even after immersion for 3 h moisture levels exceed 63%. This is similar to the findings of Brebner *(4)* and Wasp et al. *(6)*, who reported saturated wood values of 65%. We conducted two experiments with straw and found that moisture level rose from 14% as received to >80% after exposure of 3 h. This is similar to the findings of Jenkins et al. *(9)* for rice straw from California.

Absorption of water has serious implications for any process such as direct combustion that converts absorbed liquid water in the fuel into emitted water vapor in the flue gas, in that it reduces the lower heating value (LHV) of the biomass and requires more biomass per unit of heat released by combustion, an effect also noted by Yoshida et al. *(10)*. Figure 5 shows the loss in LHV and the corresponding increase in biomass that must be delivered to a direct combustion-based biomass operation at 67% moisture level. Werther et al. *(11)* note some other problems with increasing moisture in the direct combustion of biomass: reduced combustion temperature, delayed release of volatiles, poor ignition, and higher volumes of flue gas. These secondary impacts on efficiency and operability of a direct combustion unit are not considered in Fig. 5.

One can conceptually break down biomass utilization into three component cost categories: (1) field harvest of biomass, (2) transportation from the field to the biomass processing site, (3) cost of processing/conversion. For direct combustion of truck-transported biomass from harvesting of the whole forest in western Canada at or near optimum scale, the percentage and cost per megawatt-hour are as follows: category 1: 33.4%, 15.77$/MWh; category 2: 14.3%, 6.74$/MWh; and category 3: 52.3%, 24.65$/MWh *(1)*.

Since, as shown in Fig. 5, changing the moisture level of wood chips from 50% to 67% increases the requirement for field biomass in direct combustion by 78% for a given output of heat and power, it is evident that water-based pipelining of wood chips cannot be economical for direct combustion, because the increase in field harvest cost associated with the higher biomass requirement is larger than any possible transportation cost saving. For straw, so much water is taken up that the LHV is effectively zero; pipeline transport of straw to a direct combustion application would destroy the heating value of the fuel.

This impact is not true for a fuel process such as supercritical water gasification of biomass *(12—14)* that does not produce water vapor from absorbed water, since the higher heating value (HHV) value of the biomass is effectively realized by countercurrent exchange of heat between products and feed that results in condensation of produced water. The impact of absorbed water is also not an issue for fermentation of biomass, since this is a water-based process. Pipelining of biomass to fermentation processes offers the promise of larger-scale, more economic processing of ethanol, chemicals, and byproducts such as lignin. However, the pipeline design would require more detailed assessment since saccharification in the pipeline would be a logical processing alternative, and this would require temperature control during pipeline transport. This more detailed assessment is the subject of future study.

During oil immersion for 48 h, 1 kg of mixed conifer and aspen wood chips at an average 50% water content would pick up an additional 0.45 kg of oil and reach an oil level of 31%. Comparable figures for 124 hours are an uptake of 0.52 kg to reach a oil level of 34%. Direct combusting wood chips delivered in a heavy gas oil can be thought of as cofiring a mix of about two/thirds oil and one/third wood on a thermal basis. Pipeline cost would increase because of additional pumping; the increase would depend on the viscosity of the oil fraction that was selected as the transport carrier fluid.

Discussion

Pipeline transport of oil and natural gas is clearly far more economical than truck transport, even in relatively small pipelines. Three factors combine to make the transport of energy in the form of biomass far less economic:

1. The density of energy in the pipeline is far lower for biomass than for oil. The present work is based on 30% biomass by volume in a carrier liquid. Wasp et al. *(6)* based their work on 22% biomass. Brebner *(4)* and Elliott *(5)* indicated that at about 47% concentration by volume a slurry of wood chips and water cannot flow. Given the low heat content of wood per unit volume relative to oil and the low concentration of wood chips in water, the energy density in a 30% wood chip slurry is about 8% compared to oil, even based on HHV, and hence far larger pipelines are required to transport the same amount of energy.

2. The pressure drop in the pipeline is high for suspended solids in a carrier fluid. For example, Wasp et al. *(6)* indicate that at 30% concentration of wood and a velocity of 1.4 m/s, a wood chip slurry in a 214-mm-diameter pipeline has a pressure drop that is three times larger than for water alone.
3. Recycle of the carrier fluid will often be required in biomass transport by pipeline, both because large quantities of water will not be available at the inlet end and because discharge of water that has carried the biomass will, in some jurisdictions, be prohibited. This requires that a second pipeline and set of pumping stations be constructed.

In addition to these cost elements, transport of biomass for a direct combustion application by water creates a prohibitive drop in the LHV of the fuel because of absorbed water. These issues limit the application of pipeline transport of biomass to large applications that use oil as a carrier medium, or that supply a process for which the heat content of the fuel is not degraded by the requirement to remove absorbed water as vapor, such as a supercritical water gasification process.

Transport of wood chips by oil precludes firing a high percentage of biomass owing to high oil uptake by wood chips. We consider it unlikely that a two-thirds oil and one-third wood fuel mixture would have high interest today as a power plant fuel, since even a heavy gas oil fraction has too high a value as a transportation fuel precursor to be diverted into power generation.

Conclusion

Pipeline transport of truck-delivered wood chips is only economical at large capacities and medium to long distances. For a one-way pipeline, the minimum economic capacity is >0.5 million dry t/yr. For a two-way pipeline, the minimum economic capacity is >1.25 million dry t/yr. At 2 million dry t/yr, the minimum economical distance for a one-way pipeline without carrier fluid return is 75 km, and for a two-way pipeline with carrier fluid return is 470 km.

Furthermore, water transport of mixed hardwood and softwood chips causes an increase in moisture level to 65% or greater, which so degrades the LHV of the biomass that it cannot be economical for any process, such as direct combustion, that produces water vapor from water contained in the biomass. The impact on straw is greater, in that moisture levels are so high that the LHV is negative. Pipeline transport of biomass water slurries can only be utilized when produced water is removed as a liquid, such as from supercritical water gasification.

Finally, oil transport of mixed hardwood and softwood chips gives a fuel that is more than 30% oil by mass and is two-thirds oil and one-third wood on a thermal basis.

Acknowledgments

We gratefully acknowledge the Poole family and Bud Kushnir, whose financial support made this research possible. Sean Sanders of Syncrude Canada provided insight into pump size and pressure drop in the slurry pipeline and also provided heavy gas oil for the experiments. Mark Coolen, woodlands operations superintendent for Millar Western Forest Products, provided wood chips for the experiments and valuable discussions. David Williams, Chief Estimator for Bantrel (an affiliate of Bechtel), provided valuable comments concerning capital cost estimation of pipeline. Vic Lieffers and Pak Chow of the University of Alberta helped carry out the experiments. All conclusions and opinions are solely the authors and have not been reviewed or endorsed by any other party.

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