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The potential of multiproduct pipelines for sustainable biofuel transport

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ABSTRACT

As the most potential renewable energy, biofuel has become the fourth largest fuel source after coal, oil and natural gas. Promoting the extensive application of biofuel is an effective way to reduce carbon emission. At present, pipeline is one of the most efficient modes for transporting large amounts of liquid fuel over long distance. Transporting biofuel through the existing multiproduct pipelines is in line with the requirements of environmental protection, energy saving and low carbon economy. To determine the maximum transportation capacity of biofuel in a certain period is the premise of adopting multiproduct pipelines to transport biofuel. However, there are few studies on this issue. Considering the ordered pipeline capacity of clients for refined products, the limitations of existing pipeline equipment, and the transportation time limitation of biofuel, this paper develops a model for calculating the maximum transportation capacity of biofuel in pipelines. Finally, the applicability of the model is illustrated by applying it to a real-world pipeline in China. The results show that the model can reasonably calculate the maximum transportation capacity of biofuel in pipeline.

Keywords: biofuel; multiproduct pipeline; maximum transportation capacity

NONMENCLATURE

Sets	
T	Set of time nodes.
O	Set of refined products.
B	Set of biofuel.
ID	Set of depot nodes.
I	Set of all nodes and segments.
JO	Set of old batches in line.
JB	Set of batches consist of biofuel.
J	Set of all batches.
Parameters	
$d_{i,o}$	Demand of depot node *i* for product *o*(m^3).
h	Time horizon(h).
$fs_i^{\min} / fs_i^{\max}$	Minimum/maximum volume into segment (*i*,*i+1*)(m^3).
$qi^{\min} / qi^{\max}$	Minimum/maximum pumping rate of source node(m^3/h).
$qd_i^{\min} / qd_i^{\max}$	Minimum/maximum delivery flowrate of depot node *i*(m^3/h).
$qs_i^{\min} / qs_i^{\max}$	Minimum/maximum flowrate in segment (*i*,*i+1*)(m^3/h).
tr	Maximum transportation time of biofuel in the pipeline(h).
vb_j^0	Initial volume of batch *j*(m^3).
$vb^{\min}$	Minimum injection volume(m^3).
$vi^{\min} / vi^{\max}$	Minimum/maximum pumping volume of source node(m^3).
$vd_i^{\min} / vd_i^{\max}$	Minimum/maximum delivery volume of depot node *i*(m^3).
vs_i	Volumetric coordinate of node *i*()m^3.
vp	Pipeline volume(m^3).
$vf_o^{\max}$	Maximum volume of product *o* can be transferred during the horizon(m^3).
$y_{j,o}$	Binary parameter indicating batch *j* consists of product *o*.
Variables	
$CL_{t,j} / CR_{t,j}$	Left/right coordinate of batch *j*(m^3).

τ_t	Duration of time interval t(h).
T_t	Time node t(h).
TI_j^s	Starting time node of pumping operation of batch j(h).
$TD_{i,j}^e$	Ending time node of delivery operation of batch j at depot node i(h).
$VB_{t,j}$	Volume of batch j(m^3).
$VI_{t,j}$	Injection volume of batch j at source node during interval t(m^3).
$VI_{t,j,o}^p$	Injection volume of batch j of product o at source node during interval t(m^3).
$VD_{t,i,j}$	Delivery volume of batch j at depot node i during interval t(m^3).
$VD_{t,i,j,o}^p$	Delivery volume of batch j of product o at depot node i during interval t(m^3).
$VS_{t,i}$	Volume in segment (i,$i+1$) during interval t(m^3).
$SI_{t,j}$	Binary variable indicating source node is pumping batch j during interval t.
$SI_{t,j}^s$	Binary variable indicating batch j begins to be pumped into pipeline during interval t.
$SD_{t,i,j}$	Binary variable indicating depot node i is receiving batch j during interval t.
$SD_{t,i,j}^e$	Binary variable indicating depot node i ends the delivery operation of batch j during interval t.
$SP_{t,i}$	Binary variable indicating segment (i,$i+1$) is active during interval t.

1. INTRODUCTION

1.1 Background

Over these years, various countries have begun to develop renewable energy, which makes its proportion in the world energy consumption gradually increase[1]. As the most potential renewable energy, biofuel can be an alternative to traditional energy. Promoting the extensive application of biofuel is an effective way to reduce carbon emission, which satisfies the current requirements of environmental protection, energy saving and low carbon economy[2].

Among the multiple transportation modes, pipeline is the most efficient mode for transporting large amounts of liquid fuel over long distance, due to its advantages of lower operation costs, higher reliability, and less environmental pollution[3, 4]. So far, the total length of pipelines continues to grow around the world, and many countries have formed relatively complete pipeline networks for liquid fuel. At present, giant oil industries usually commission pipeline operator to transport refined products to the depots constructed by industries. The enterprises submit their requirements to pipeline operator, and then the pipeline operator will arrange reasonable schedule[5, 6]. With the increasing focus on the climate change and environmental pollution around the world, demand for refined products is slowing down, resulting in the surplus of pipeline transportation capacity. Adopting the surplus transportation capacity of pipeline to transport biofuel is a potential mode that can not only improve the revenue of pipeline operator, but also help oil industries to reduce carbon emissions. Therefore, it is of great significance to propose a method to reasonably calculate the maximum capacity of pipeline for transporting biofuel.

1.2 Related work

Currently, the related studies mainly focus on the planning and resource allocation of biofuel supply chain at the strategic and tactical levels and the pipeline scheduling at the operation level.

Many studies have been carried on the design and planning of biofuel supply chain from multiple aspects, including feedstock selection, facility location, capacity design, technology selection, resource allocation and profit distribution[7-9]. However, these studies ignored the full use of the existing petroleum infrastructure, making the construction cost of supply chain too expensive. Aiming at this issue, some studies have discussed how to design a biofuel supply chain by adopting existing petroleum infrastructure[2, 10]. Their findings showed that the biofuel supply chain combined with existing petroleum infrastructure can reduce capital costs and total annualized costs.

In view of the pipeline scheduling problem, many scholars have conducted extensive research on the scheduling of multiproduct pipelines with different structures[11-13]. Considering the requirements of clients, limitations of pipeline equipment and operation technology, the existing studies usually establish the models with the objective function of maximizing clients' satisfaction or minimizing operation cost of pipeline operator, so as to obtain the schedule that satisfies clients' demand.

Overall, there are few studies on the calculation method of pipeline surplus capacity. In the production site, the operators only use volume addition and subtraction as the basis for calculating surplus capacity. The transportation and storage cycle of biofuel is short, so it has strict requirements for transportation time and environment. When calculating the maximum capacity of pipeline for transporting biofuel, not only the ordered pipeline capacity of clients for refined products, but also the coupling relationship of many factors such as the physical properties of products, equipment limitations, and transportation time limitation should be considered. It is difficult to achieve accurate calculation by existing method.

2. MODEL REQUIREMENT

To calculate the maximum capacity of pipelines to transport biofuel in a certain period, this paper proposes a mixed integer linear programming (MILP) model with considering the demand of clients for refined products, the limitations of existing pipeline equipment and transportation time of biofuel.

Given:

- The requirements of clients for refined products.
- The initial products in pipeline and sequence of pumping batches.
- Depot information, including their locations, limitations of pumping rate and delivery flowrate.
- Pipeline information, including the segment volume and flowrate limitations.

Determine:

- The maximum capacity of pipelines to transport biofuel.
- The number of depots that can receive biofuel.

Assumptions:

- Products transported in the pipeline are incompressible.
- Due to the physical difference of products, the contamination will occur between two adjacent batches when moving in a pipeline. The mixed section is considered as an interface.
- Pumped products flow unidirectionally from the source node to the downstream depots.
- The biorefinery has sufficient capacity to produce biofuel.

3. MATHEMATICAL MODEL

3.1 Objective function

The objective function discussed in this paper is to maximize the injection volume of biofuel, as shown in Eq.(1).

$$\max f = \sum_{t<|T|}\sum_{j\in J}\sum_{o\in B} VI_{t,j,o} \quad (1)$$

3.2 Time interval

The time interval τ_t starts at time node T_t and ends at time node T_{t+1}, as stated in Eq.(2). Eq.(3) indicates that the sum of intervals should not be greater than the given time horizon h.

$$T_t = T_{t-1} + \tau_{t-1} \qquad \forall t \in T \quad (2)$$

$$\sum_{t<|T|} \tau_t \le h \quad (3)$$

3.3 Requirement for transporting biofuel

The starting time node of pumping operation of batch j can be determined through Eqs.(4)-(6). Also, Eqs.(7)-(9) can calculate the ending time node of delivery operation at depot node i. Due to the physical limitation of biofuel, it cannot be transported in pipeline for a long time, as shown in Eq.(10).

$$SI^s_{t,j}\,|_{t=1} \ge SI_{t,j}\,|_{t=1} \qquad \forall j \in JB \quad (4)$$

$$SI^s_{t+1,j} \ge SI_{t+1,j} - SI_{t,j} \qquad \forall j \in JB, t <|T| \quad (5)$$

$$(SI^s_{t,j} - 1)h + T_t \le TI^s_j \le (1 - SI^s_{t,j})h + T_t \qquad \forall i \in ID, j \in JB, t <|T| \quad (6)$$

$$SD^e_{t,i,j}\,|_{t=|T|-1} \ge SD_{t,i,j}\,|_{t=|T|-1} \qquad \forall i \in ID, j \in JB \quad (7)$$

$$SD^e_{t,i,j} \ge SD_{t,i,j} - SD_{t+1,i,j} \qquad \forall i \in ID, j \in JB, t <|T| \quad (8)$$

$$(SD^e_{t,i,j} - 1)h + T_{t+1} \le TD^e_{i,j} \le (1 - SD^e_{t,i,j})h + T_{t+1} \qquad \forall i \in ID, j \in JB, t <|T| \quad (9)$$

$$TD^e_{i,j} \le TI^s_j + tr \qquad \forall i \in ID, j \in JB \quad (10)$$

3.4 Batch tracking

The right coordinate of batch j can be calculated through summing the volume of all batches in the pipeline(i.e., Eq.(11)), while the left coordinate can be computed by subtracting its batch volume in line from the right coordinate(i.e., Eq.(12)). The total volume of all batches inside line should be equal to the line volume, as stated in Eq.(13). The volume of each batch should follow the volume balance in Eq.(14). It shows that the volume of batch j at time node t is equal to the volume at previous time node plus the injection volume of source node and minus the delivery volume of depot nodes during interval $t-1$.

$$CR_{t,j} = \sum_{j'\ge j} VB_{t,j'} \qquad \forall j \in J, t \in T \quad (11)$$

$$CL_{t,j} = CR_{t,j} - VB_{t,j} \qquad \forall j \in J, t \in T \quad (12)$$

$$\sum_{j\in J} VB_{t,j} = vp \qquad \forall t \in T \quad (13)$$

$$VB_{t,j} = vb^0_j\,|_{t=1} + VB_{t-1,j} + VI_{t-1,j} - \sum_{i\in ID} VD_{t-1,i,j} \qquad \forall j \in J, t \in T \quad (14)$$

3.5 Pumping operation

Since source node must be an initial node of a line, its coordinate is set as zero. Therefore, if a new batch is pumped into the line during interval *t*, its left coordinate must be zero at start time of the interval, as seen in Eq.(15). Otherwise, this constraint will be relaxed. Eq.(16) shows that the source node can only pump one batch during any time interval. If source node is active during interval *t*, batch *j* receives the volume at a pumping rate should be within the range, as imposed by Eqs.(17)-(18). During the whole horizon, the injection volume of batch *j* should be greater than the minimum value(i.e., Eq.(19)). The total volume of batch *j* pumped into line can be computed by summing the product-disaggregated variable $VI_{t,j,o}^{p}$, as stated in Eq.(20).

$$CL_{t,j} \le (1 - SI_{t,j})vp \qquad \forall j \in J, t <|T| \quad (15)$$

$$\sum_{j \in J} SI_{t,j} \le 1 \qquad \forall t <|T| \quad (16)$$

$$SI_{t,j} vi^{\min} \le VI_{t,j} \le SI_{t,j} vi^{\max} \qquad \forall j \in J, t <|T| \quad (17)$$

$$\frac{\sum_{j \in J} VI_{t,j}}{qi^{\max}} \le \tau_t \le \frac{\sum_{j \in J} VI_{t,j}}{qi^{\min}} + (1 - \sum_{j \in J} SI_{t,j})h \qquad \forall t <|T| \quad (18)$$

$$vb^{\min} \le \sum_{t<|T|} VI_{t,j} \qquad \forall j \in J \setminus JO \quad (19)$$

$$VI_{t,j} = \sum_{o \in O \cup B} VI_{t,j,o}^{p} \qquad \forall j \in J, t <|T| \quad (20)$$

3.6 Delivery operation

The depot node *i* can receive batch *j*, if its left and right coordinates at the start and end of interval *t* can satisfy Eqs.(21)-(23). Each depot node can only receive at most one batch during an interval, as stated by Eq.(24). Eqs.(25)-(26) control the size that can be delivered from batch *j* to active depot node *i*. The total volume of batch received from line can be computed by summing the product-disaggregated variable $VD_{t,i,j,o}^{p}$, as stated in Eq.(27).

$$CL_{t,j} - vs_i \le (1 - SD_{t,i,j})(vp - vs_i) \qquad \forall i \in ID, j \in J, t <|T| \quad (21)$$

$$CL_{t+1,j} - vs_i \le (1 - SD_{t,i,j})(vp - vs_i) \qquad \forall i \in ID, j \in J, t <|T| \quad (22)$$

$$vs_i - CR_{t,j} \le (1 - SD_{t,i,j})vp \qquad \forall i \in ID, j \in J, t <|T| \quad (23)$$

$$\sum_{j \in J} SD_{t,i,j} \le 1 \qquad \forall i \in ID, t <|T| \quad (24)$$

$$SD_{t,i,j} vd_i^{\min} \le VD_{t,i,j} \le SD_{t,i,j} vd_i^{\max} \qquad \forall i \in ID, j \in J, t <|T| \quad (25)$$

$$\frac{\sum_{j \in J} VD_{t,i,j}}{qd_i^{\max}} \le \tau_t \le \frac{\sum_{j \in J} VD_{t,i,j}}{qd_i^{\min}} + (1 - \sum_{j \in J} SD_{t,i,j})h \qquad \forall i \in ID, t <|T| \quad (26)$$

$$VD_{t,i,j} = \sum_{o \in O \cup B} VD_{t,i,j,o}^{p} \qquad \forall i \in ID, j \in J, t <|T| \quad (27)$$

3.7 Batch-product assignment

If $y_{j,o}$ equals to 0, Eq.(28) enforces all disaggregated variables about volume involving batch *j* and product *o* to be zero.

$$\sum_{t<|T|} VI_{t,j,o}^{p} + \sum_{t<|T|} \sum_{i \in ID} VD_{t,i,j,o}^{p} \le y_{j,o} vf_o^{\max} \qquad \forall j \in J, o \in O \cup B \quad (28)$$

3.8 Demand of depots

Eq.(29) and Eq.(30) respectively show that the total delivery volume of biofuel and refined products at depot node *i* should satisfy the demand of clients.

$$\sum_{t<|T|} \sum_{j \in J} VD_{t,i,j,o}^{p} \ge 0 \qquad \forall i \in ID, o \in B \quad (29)$$

$$\sum_{t<|T|} \sum_{j \in J} VD_{t,i,j,o}^{p} = d_{i,o} \qquad \forall i \in ID, o \in O \quad (30)$$

3.9 Flowrate limitations of pipeline segments

The flowrate crossing segment (*i*,*i+1*) during interval *t* can be computed through the volume balance presented in Eqs.(31)-(32). The volume entering the downstream segment can be computed by subtracting the volume received by depot node from the volume leaving the upstream segment. During each interval, the flowrate in an active segment should be kept in a feasible range, as imposed by Eqs.(33)-(34).

$$VS_{t,i}|_{i=1} = \sum_{j \in J} VI_{t,j} \qquad \forall t <|T| \quad (31)$$

$$VS_{t,i} - \sum_{j \in J} (VD_{t,i+1,j}) = VS_{t,i+1} \qquad \forall i <|I|, t <|T| \quad (32)$$

$$SP_{t,i} fs_i^{\min} \le VS_{t,i} \le SP_{t,i} fs_i^{\max} \qquad \forall i <|I|, t <|T| \quad (33)$$

$$\frac{VS_{t,i}}{qs_i^{\max}} \le \tau_t \le \frac{VS_{t,i}}{qs_i^{\min}} + h(1 - SP_{t,i}) \qquad \forall i <|I|, t <|T| \quad (34)$$

4. CASE STUDY

4.1 Basic data

In this paper, the model is applied to a real multiproduct pipeline system in China to calculate its maximum capacity to transport biofuel in 10-day horizon, based on the client's demand of refined products. The length of this pipeline system is 376km, involving one source node(N1) and five depot nodes(N2-N6), as shown in Fig.1. Three types of refined products(P1-P3) and one type of biofuel(P4) are conveyed from source node to depot nodes. At initial time, the pipeline is full of P1 and P2. The optimum pumping sequence is P2-P4-P3-P2-P1. Table 1 shows the details of the pipeline system, including the length and flowrate limitations of each segment. The operation flowrate limitations of nodes are shown in Table 2. Table 3 presents demand volume of refined products at each depot node. All cases are solved by Gurobi 9.0.3 MILP solver.

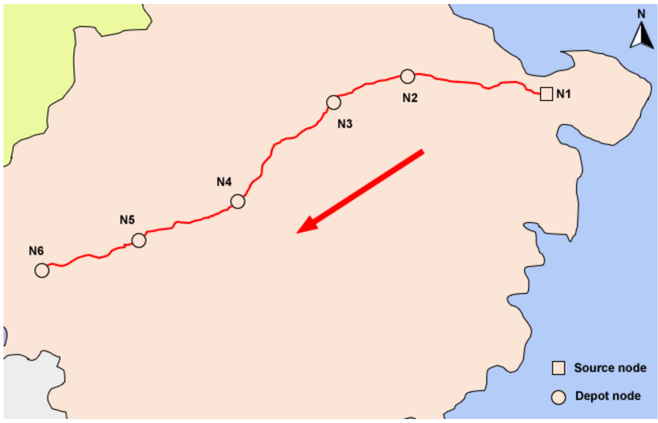

Fig 1 The studied multiproduct pipeline system.

Table 1 Basic data of pipeline

Segment	Length(km)	Upper limit (m^3/h)	Lower limit (m^3/h)
N1-N2	130	1,250	700
N2-N3	89	1,100	500
N3-N4	51	1,100	--
N4-N5	67	1,100	--
N5-N6	39	600	--

Table 2 Operation flowrate limitations of nodes

Node	Upper limit (m^3/h)	Lower limit (m^3/h)
N1	1,250	700
N2	750	150
N3	250	100
N4	600	150
N5	600	150
N6	600	150

Table 3 Demand volume of refined products at depot nodes

Node	P1(m^3)	P2(m^3)	P3(m^3)
N2	12,000	19,000	10,000
N3	5,500	5,000	2,500
N4	15,000	30,000	14,000
N5	14,000	20,000	8,500
N6	36,000	20,000	8,000

4.2 Results and discussion

Through solving the model, it can be obtained that the maximum capacity of the pipeline to transport biofuel within 10-day horizon is 53,490m^3. The schedule is shown in Fig.2, which presents the migration of products in the pipeline and operations of each node during the horizon. In the figure, the vertical axis and the horizontal axis respectively represent the length and time. Different colors represent different products. The rectangle bars denote the operations of batches at each node, and their width represents the size of flowrate. Besides, the black oblique line represents the batch migration. As shown in Fig.2, the biofuel can be transported to N2, N3 and N4 under the limitations of client's demand for refined products, pipeline equipment and transportation cycle of biofuel.

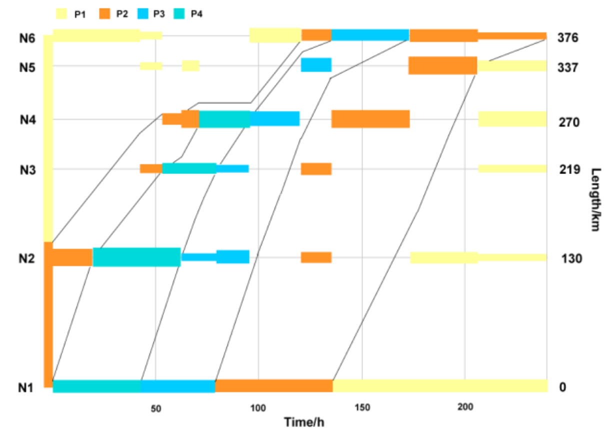

Fig 2 Transportation scheme under base scenario.

Then, we analyze the impact of demand variation of refined products on the maximum capacity of pipeline to transport biofuel. The pipeline capacity for transporting biofuel under different scenarios is shown in Fig.3. In the figure, the horizontal axis represents the scenario corresponding to the variation ratio, and the vertical axis represents the maximum transportation capacity. As the demand of refined products grows, the pipeline capacity for transporting biofuel gradually declines. Meanwhile, we also analyze the transportation price of biofuel in the scenario of demand reduction of refined products. To compensate for the economic losses caused by decline of refined products demand, pipeline operator needs to set different transportation prices of biofuel for different scenarios. Table 4 presents the transportation prices under base scenario(S_0) and demand reduction scenarios respectively. In this paper, it is assumed that transportation price of biofuel under base scenario is consistent with that of refined products. Taking the second line in table 4 as an example, if refined product demand is reduced by 5% compared to base scenario, the transportation price of biofuel is at least 0.18CNY/(km·m^3).

Table 4 Transportation prices of biofuel under different scenarios

Scenarios	Ratio	Capacity(m^3)	Price(CNY/(m^3·km))
S_0	0	53,490	0.15
$S_{-5\%}$	-5%	54,342	0.18
$S_{-10\%}$	-10%	57,121	0.20
$S_{-15\%}$	-15%	57,121	0.23

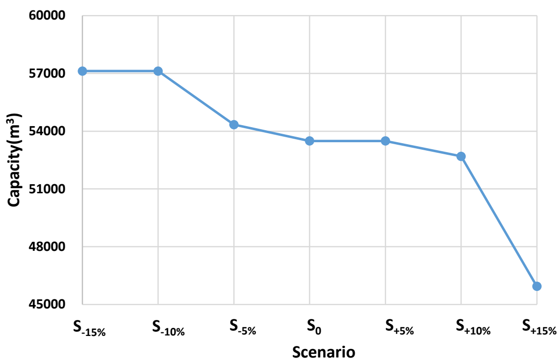

Fig 3 Pipeline capacity for transporting biofuel under different scenarios.

5. CONCLUSION

On the basis of the ordered pipeline capacity of clients for refined products, the operation limitations of equipment, and time limitation for transporting biofuel, this paper puts forward a MILP model to calculate the capacity of pipelines for transporting biofuel with the objective function of maximum injection volume of biofuel. Finally, a real-world multiproduct pipeline system in China is presented to illustrate the applicability of the proposed model. The results show that the model can reasonably calculate the maximum capacity of biofuel through pipeline transportation and detailed schedule within a given horizon. Meanwhile, the model also can provide advice for pipeline operator to set transportation price for biofuel. For the future work, the authors intend to introduce more realistic operation constraints into the model so as to calculate the capacity more accurately.

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